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Research Article

Verification of Maize-Haricot Bean Intercropping Patterns for Crop Productivity and Soil Fertility Improvement in Sibu Sire District, Western Oromia Region, Ethiopia

Temesgen Chimdessa*, Chaltu Regasa, Mintesinot Desalegn, Chalsissa Takale, Naferom Negesa

Oromia Agricultural Research Institute, Nekemte, Ethiopia

Abstract

Maize-haricot bean intercropping is one of the best agronomic practices in Ethiopia in general and at study area particularly. This trial in Sibu Sire district was aimed to verify maize-haricot bean intercropping pattern. The treatments were Control/without intercropping (C); Farmers practiced intercropping pattern (FPIP) and Research based intercropping pattern (RBIP). The trial was conducted in the year 2024 main cropping season on purposively selected farmers' fields across the district. The treatments were replicated 3 times with RCBD design. Soil test based inorganic fertilizer rate was used. Soil and agronomic data were collected and analyzed. Yields and yields related parameters of maize and haricot bean were collected and analyzed. Except Plant heights, all other collected intercropped haricot bean parameters were significantly influenced by the treatments while the maize was not. Intercropping of Ibado bean variety planted during maize planting at two sides of maize rows could increases biomass and grain yields of haricot bean by about 40.59 and 48.56%, respectively compared to farmers practiced intercropping. It also resulted the highest net income (187081 birr /ha), LER (1.58) and LEC (0.63) from the former study during technology generation. Therefore, it should be recommended for farmers in the study area and similar agroecology.

Keywords

Haricot Bean, Intercropping, Maize, Pattern, Sibu Sire, Verification

1. Introduction

Agriculture plays a central role in the Ethiopian economy, contributing significantly to national GDP and providing livelihoods for the majority of the population [1]. The sector not only sustains the livelihoods of most of the population but also plays a critical role in ensuring food security. However, in Ethiopia and across Sub-Saharan Africa, declining soil fertility is frequently the main challenge affecting agricultural productivity [2, 3]. In developing countries, intensive agricultural practices often lead to soil degradation due to improper use of inorganic fertilizers and a lack of organic fertilization [4].

Inorganic fertilizers can alleviate soil fertility limitations and improve crop yields. However, their use is often restricted due to high cost, limited availability, and inefficient management practices. As a result, many smallholder farmers are unable to apply recommended fertilizer rates [5]. In addition, ex-

*Correspondence: Temesgen Chimdessa (temesgenchimdessa468@gmail.com)

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cessive reliance on chemical nitrogen fertilizers has raised increasing global concerns due to both economic and environmental impacts. Consequently, the development of cost-effective and environmentally sustainable agricultural practices is essential for improving productivity while maintaining soil health in rain-fed farming systems [6].

In smallholder farming systems, cereal-legume intercropping is widely recognized as an effective strategy for improving crop productivity and resource-use efficiency. Intercropping enhances the utilization of common resources, consisting sunlight, water, nutrients, and space, thereby increasing land productivity compared with monocropping systems [7]. Maize-haricot bean intercropping supports smallholder farming by improving nitrogen availability, providing higher protein content, and optimizing spatial and temporal resource utilization to increase land productivity [8]. Legumes, such as common bean (bush and climbing types), soybean, groundnut, faba bean, and field pea, are commonly intercropped with major cereals such as maize and sorghum to enhance soil fertility and optimize resource use [9]. In the western Oromia Region, haricot bean is commonly intercropped with major cereals such as maize and sorghum to enhance productivity and soil fertility.

Several previous studies have demonstrated that cereal-legume intercropping systems can increase land productivity, improve nutrient cycling, and enhance farm profitability under controlled experimental conditions [7, 10, 11]. However, most of these studies were focused on single agronomic factors in isolation (planting density, variety, or planting time separately), whereas the combined interactive effects of these factors on soil fertility, system productivity, and economic performance remain poorly understood, particularly in the high-rainfall Nitisol regions of western Oromia [10]. This lack of integrated, location-specific information constrains the development of evidence-based recommendations and limits the productivity of maize-haricot bean intercropping in Sibu Sire district. Thus, there is a clear need for systematic research to generate location-specific agronomic recommendations on optimum haricot bean planting density, suitable bean varieties, and appropriate planting time for maize-haricot bean intercropping in Sibu Sire district.

To implement scientific cereal legume intercropping, research was conducted for two main cropping season (2023 and 2024) in the Sibu Sire district by the Nekemte Soil Research Center. However, before the findings can be popularized, demonstrated, or scaled up to stakeholders, careful evaluation and verification of the results are essential. Such verification is mandatory to ensure reliable recommendations and successful adoption of the technology. Therefore, this study was designed with the following objectives:

1) To verify the recommended maize- haricot bean intercropping pattern in Sibu Sire district.
2) To create awareness for stalk holders about use of cereal-legume intercropping for production and soil fertility improvement.

2. Materials and Methods

2.1. Description of the Study Area

The study area, Sibu Sire District, is located about 270 km west of the capital city of Ethiopia, Finfinne. It lies between 8°56' to 9°23' N latitudes and 36°35' to 36°56' E longitudes (Figure 1). The altitude of the district varies from 1336 to 2500 meters above sea level. It has an estimated area of 1,132.51 km. About 74.2% of its surface area belongs to Mid-altitude 7.53% of the land is highland agro climate and the remaining 18.27% is classified as low land agro climate. The mean annual temperature and mean annual rain fall is 250 ^{O}C and 1050 mm, respectively [11].

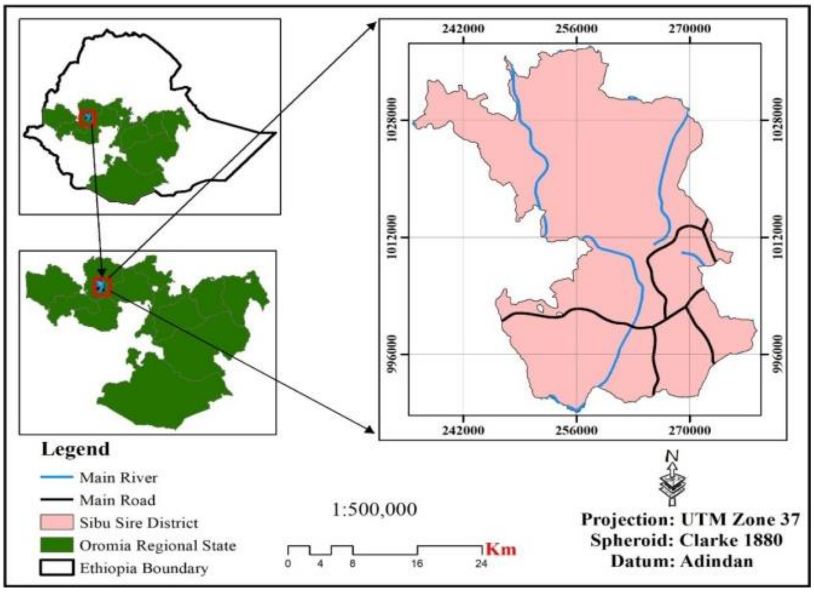

Figure 1. *Location map of the study area.*

The terrain is generally undulating to rolling plains. The major soil types are generally described as Nitisols according to FAO soil classification system [12]. This soil is characterized as deep, well-drained, red, tropical soils with diffuse horizon boundaries and a clay-rich nitic subsurface horizon. In general, this soil is highly weathered, well drained, clay in texture and strongly to moderately acidic in reaction [13]. The major annual and perennial crops grown in the study area are maize (Zea mays L.), sorghum (Sorghum bicolor L.), teff (Eragrostis tef), hot pepper (Capsicum frutescence L.), sweet potato (Ipomoea batatas L.), coffee (Coffe arabica L.), and sugarcane (Saccharum officinarum L.) [14].

2.2. Treatments and Experimental Design

The trial was conducted on five purposively selected farmers' fields in Sibu Sire district. Farmers were selected based on their willingness to participate, accessibility of the field, and soil phosphorus status (less than p critical level). Appropriate Improved maize variety ("*BH*-549*"*) was used. The experimental plots were plowed and prepared according to farmers' conventional farming practice. The soil test crop response-based fertilizer recommendation was used. The optimum N, phosphorus critical and requirement factor were 138 kg/ha, 10 and 20.63 respectively. The experiment consisted of three treatments: sole maize planting (Sole), farmers practiced intercropping pattern (FPIP), and research-based intercropping pattern (RBIP). Research based intercropping pattern is intercropping haricot bean variety (Ibado), density (two side planting which is 88,888 plant ha^{-1}) and time of intercropping (during maize planting.

The experiment was arranged using a randomized complete block design (RCBD), where the participating farmers' fields were considered as blocks to account for field variability among locations. Each treatment was replicated three times within each block. This design allowed the evaluation of treatment effects while controlling for variability in soil properties and management conditions across farmers' fields. The plot size was 10 m × 10 m. Plots within blocks were separated by 0.5 m, while blocks were separated by 1 m pathways.

Maize and haricot bean were planted during the main cropping season on (25 may 2024). Harvesting of haricot bean was carried out on (20 August 2024), while maize was harvested on (20 September 2024). Maize was planted with 75 cm rows and 30 cm between plants. The beans were planted 15 cm away from maize rows for research-based intercropping while in the rows of maize for farmers practiced intercropping. Nitrogen fertilizer was applied in the form of urea in two splits (1/3 at planting and 2/3 at three weeks after planting) while all recommended P fertilizer was applied at planting.

2.3. Soil Sampling, Preparation and Analysis Procedures

Soil samples were collected from each experimental site before planting and after crop harvest to evaluate changes in soil chemical properties. Prior to planting, soil samples were collected from the experimental fields at a depth of 0-20 cm using a soil auger. From each field, five subsamples were taken randomly following a zigzag sampling pattern across the plot area. These subsamples were thoroughly mixed to form one composite soil sample representing each experimental field.

Similarly, after crop harvest, soil samples were collected from each treatment plot at the same depth (0-20 cm). Five subsamples were taken from different points within each plot and composited to obtain one representative sample per plot. The collected soil samples were air-dried, gently crushed, and passed through a 2-mm sieve prior to laboratory analysis.

The prepared samples were analyzed for soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (Av.P), exchangeable acidity, exchangeable Ca, exchangeable Mg, and cation exchange capacity (CEC) using standard laboratory procedures.

2.4. Data Collection and Analysis

Important yield and yield related parameters of both components like; Plant height (cm), Cob length (cm), Number of seeds per cob (No); Number of branches per plants (cm), Number pods per plant (No), Number of seeds per pods (No), biomass yield (kg/ha) and grain yield (kg/ha) were collected and analyzed. One composite sub-sample from each of five farmer's sites before planting and from each plot after harvesting were collected for the determination of important soil properties. All data recorded and collected were subjected to the procedure of analysis of variance (ANOVA) using SAS software program. The comparisons among treatment means were employed by using Least Significance Difference (LSD) at 5% significant level.

3. Results and Discussions

3.1. Soil Properties Before Planting and After Harvest Under Different Treatments

The mean soil pH, organic C, total N, Available P, exchangeable acidity, exchangeable Ca, exchangeable Mg and CEC before and after harvest were presented in (Table 1). The initial soil condition before planting provides the baseline for evaluating treatment-induced changes. The soil was strongly acidic (pH 4.94), with moderate levels of organic carbon (2.43%) and total nitrogen (0.21%), low available phosphorus (6.40 ppm), relatively high exchangeable acidity (1.98 cmol(+)/kg), and high CEC (25.71 cmol(+)/kg). These characteristics are typical of many tropical soils under continuous cultivation, where nutrient mining, erosion, and limited organic matter inputs contribute to acidification and nutrient depletion [15, 16].

The results of after harvest soil chemical properties indicated that both intercropping patterns improved most soil fertility characteristics of experimental sites as compared to sole maize planting and before planting soil parameters (Table 1). The greatest positive most fertility characteristics of experimental soil were obtained from research based recommended intercropping patterns as compared to both farmers practiced intercropping and sole maize planting. Soil pH increased from 4.94 (strongly acidic) to 5.40 under all treatments (+9.3%). This improvement indicates a reduction in active acidity and exchangeable Al^{3+}, consistent with the sharp drop in exchangeable acidity. According to [16], increases in soil pH often result from organic matter decomposition releasing basic cations and reduced Al^{3+} toxicity. Research based intercropping patterns intercropping patterns improved organic carbon, Total Nitrogen, Available Phosphorus, Exchangeable Acidity, Exchangeable Ca and Exchangeable Mg by about +26.3 +23.8, +10.3, -69.7, +11.9% and +3.9% respectively as compared to before planting soil properties.

The rise in pH is consistent with findings by [17], who reported that intercropping increases soil pH through increased organic matter and enhanced cation exchange. The highest improvement of organic carbon under research based intercropping pattern indicates greater biomass return and decomposition. Organic carbon increases reflect an improvement in soil organic matter status. According to [18] findings, organic inputs improve Soil structure, Microbial activity, Nutrient cycling. Research based on intercropping patterns appears to supply more organic residues, leading to better carbon stabilization. Nitrogen is primarily stored in organic matter; TN closely follows OC increases. Research based intercropping pattern produced the highest TN increase due to enhanced nitrogen mineralization. According to [19], treatments with higher biomass return enhance soil N through decomposition and microbial turnover. The decline in P under the sole maize system shows the risk of nutrient mining and long-term soil degradation under monocropping without replenishment. While the increased available P, under intercropping is likely because organic inputs release P during decomposition, higher pH reduces P fixation by Fe and Al oxides and Root organic acids mobilize P [20].

Lower EA means reduced Al^{3+} and H^{+} toxicity, improving root growth [15]. Organic matter complexes Al^{3+} and reduces acidity. Increases in Ca and Mg reflect Organic inputs releasing base cations. Reduced acidity improving cation retention [16].

The slight variation in soil Cation Exchange Capacity (CEC) among treatments may be attributed to differences in crop residue contribution, root activity, and nutrient cycling under the various intercropping arrangements. Intercropping systems, particularly those involving legumes such as haricot bean, can influence soil chemical properties through biological nitrogen fixation, root exudates, and the addition of organic residues to the soil. Intercropping systems are widely reported to enhance soil fertility through greater biomass return, improved nutrient use efficiency, and increased soil biological activity [10, 21]. These processes may enhance soil organic matter content and consequently improve the soil's capacity to retain exchangeable cations. However, because CEC is a relatively stable soil property and the experiment was conducted over a short period, the differences observed among treatments were small. Similar observations have been reported in intercropping systems where short-term management practices caused only slight changes in soil CEC [18].

Table 1. *Soil Chemical Properties Before Planting and after harvest under Different treatments.*

	Soil chemical properties							
	pH (H_2O)	OC (%)	TN (%)	AV.P (ppm)	EA cmol(+)/Kg	E.Ca cmol(+)/Kg	E.Mg cmol(+)/Kg	CEC cmol(+)/Kg
Before planting	4.94	2.43	0.21	6.40	1.98	10.10	9.50	25.71
Treatments (after harvest)								
Sole	5.40	2.80	0.24	6.10	0.59	10.4	9.50	26.71
FPIP	5.40	2.94	0.25	6.90	0.63	11.2	9.70	26.78
RBIP	5.40	3.07	0.26	7.06	0.60	11.3	9.87	26.03

Where pH = power of hydrogen; OC = Organic carbon; TN = Total Nitrogen; Av.P = Available Phosphorus; EA = Exchangeable acidity; E. Ca = Exchangeable calcium; E. Mg = Exchangeable magnesium; CEC = Cation exchange capacity; FPIP = Farmers practiced intercropping pattern and Research based intercropping pattern

3.2. Effect of the Treatments on Growth and Yield Related Parameters of Maize

Plant Height (PH):

Maize Plant height was not significantly influenced by the treatments (P > 0.05). Mean plant height ranged from 206.39 cm under farmers practiced intercropping system to 221.39 cm under the sole maize planting, while research-based intercropping recorded 220.11 cm (Figure 2). Although sole maize produced slightly taller plants, the differences among treatments were smaller than the LSD (25.14 cm) and therefore not statistically significant at the 5% probability level.

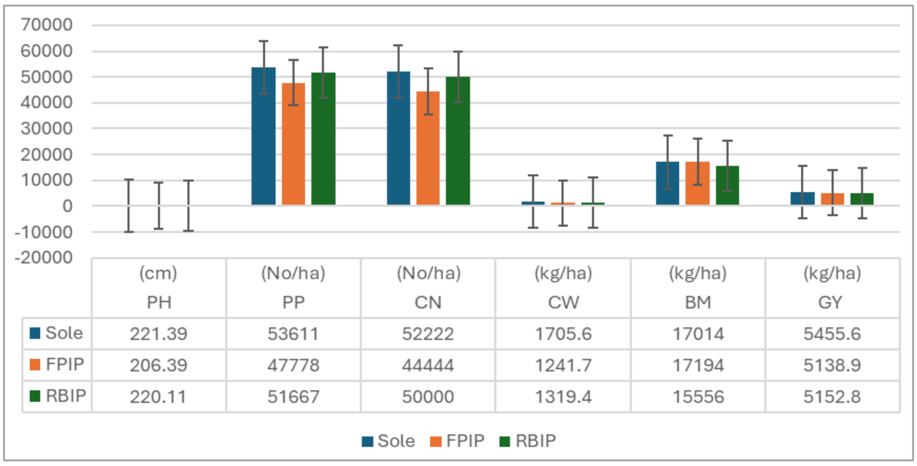

Figure 2. *Yields and yield related parameters of maize as affected by the treatments.*

Where Sole = sole maize planting FPIP = farmers practiced intercropping pattern; RBIP = research based intercropping pattern; Sig = significance; LSD = least significance difference; NS= Not significant, CV = Coefficient of variation; PH = plant height; PP = Plant population density; CN = cob number; CW = cob weight; BM = biomass yield and GY = grain yield

The lack of a significant response of plant height to intercropping agrees with previous findings that maize height is often stable even when grown with companion crops, because height is strongly genetically controlled and less sensitive to moderate competition [10, 21]. The slightly reduced height under farmers practiced intercropping may reflect higher competition for light, nutrients, or moisture resulting from farmers' less-optimized intercropping patterns. By contrast, research based intercropping patterns which are structured to minimize spatial competition, maintained height values close to those of sole maize, consistent with research showing that well-designed intercropping reduces competitive stress [22].

Plant Population (PP): Maize plant population density also showed no significant differences among treatments (P > 0.05). The mean maize plant population varied between 47,778 plants ha^{-1} (farmers practiced intercropping patterns) and 53,611 plants ha^{-1} (Sole maize planting), with research based intercropping patterns at 51,667 plants ha^{-1} (Figure 2). The similarity in maize plant population indicates good crop establishment across treatments and suggests that the intercropping patterns used did not adversely affect maize emergence. This finding agrees with [23], who reported that properly spaced intercropping systems do not negatively influence maize stand count.

Cob Number (CN): Maize cob number per hectare ranged from 44,444 (farmers practiced intercropping patterns) to 52,222 (Sole maize planting), but again the differences were not statistically significant (P > 0.05) (Figure 2). Farmers practiced intercropping patterns tended to produce fewer cobs (−14.9% relative to Sole), while research based intercropping patterns were closer to Sole (−4.2%). Cob number is strongly associated with plant vigor and resource availability during the early reproductive phase [24]. The lower maize cob number under farmers practiced intercropping patterns likely reflects the less optimal plant arrangement and greater competitive interactions characteristic of farmers' traditional methods. However, due to experimental variability (CV = 10.67%), these numerical differences were not statistically reliable.

Maize Cob Weight (CW): Maize cob weight exhibited relatively large numerical differences among treatments 1705.6 kg ha^{-1} (Sole maize planting), 1241.7 kg ha^{-1} (farmers practiced intercropping), and 1319.4 kg ha^{-1} (research based intercropping patterns) (Figure 2). Farmers practiced intercropping and research based intercropping patterns recorded 27.2% and 22.6% lower maize cob weight than Sole, respectively, but the variation was not statistically significant (P > 0.05). Researchers have reported that cob weight is highly responsive to stress and competition, especially under intercropping [25, 26], the numerical reduction in farmers practiced intercropping may reflect competitive pressure, but the non-significance implies that the experiment could not detect a treatment-driven effect with confidence.

Aboveground Biomass (BM): The maize total biomass yield ranged from 15,556 kg ha^{-1} (research based intercropping system) to 17,194 kg ha^{-1} (farmers practiced intercropping system), with sole maize at 17,014 kg ha^{-1} (Figure 2). These differences were also non-significant at the 5% level. Interestingly, farmers practiced intercropping systems which produced slightly higher biomass (+1.06% relative to Sole), though it did not translate into higher grain yield or cob traits. This aligns with findings that biomass can remain high in intercropping systems even when reproductive yield declines, due to increased vegetative competition (Ghosh, 2004).

Grain Yield (GY): Maize grain yield showed no significant response to the treatments ($P > 0.05$), despite numerical differences (Figure 2). The highest maize grain yield was obtained under sole maize (5455.6 kg ha^{-1}), followed by research based (5152.8 kg ha^{-1}) and farmers practiced intercropping system (5138.9 kg ha^{-1}). The maximum difference (316.7 kg ha^{-1}) was far below the LSD (1208.2 kg ha^{-1}), confirming the statistical similarity of yields across treatments. This result is consistent with previous studies showing that maize yields under well-managed intercropping systems are often comparable to sole cropping [10, 11]. The slightly better performance of research based recommended intercropping systems relative to local practiced supports the principle that intercrop design strongly affects maize performance, and optimized arrangements reduce competition [27].

Harvest Index (HI): Maize harvest index ranged from 30.10% (farmers practiced) to 33.96% (research based recommended intercropping system), with sole at 32.46% (Figure 2). Differences were not statistically significant ($P > 0.05$). HI values indicate the proportion of assimilates allocated to grain relative to biomass. The slightly higher HI in RBIP suggests more efficient partitioning, which may reflect improved spatial arrangements reducing competitive stress [24]. However, due to non-significant results, this trend should be interpreted cautiously.

3.3. Effect of the Treatments on Growth and Yield Related Parameters of Haricot Bean

The results revealed that all traits except plant height significantly responded to the intercropping patterns, with research based intercropping patterns consistently outperforming farmers practice intercropping system in branches per plant, pods per plant, seeds per pod, biomass yield, and grain yield.

Haricot Bean Plant Height: Although research based recommended intercropping system produced slightly taller plants (38.38 cm) compared to FPIP (37.07 cm), the difference was not statistically significant (Table 2). This suggests that plant height is a relatively stable trait under the current intercropping arrangements.

Similar observations have been reported in previous studies, where plant height showed limited sensitivity to cropping pattern but yield components varied significantly depending on management practices. While haricot bean height varied among genotypes, it had weak correlation with final grain yield compared with pods per plant and seeds per pod [28]. Likewise, a study in Yabello indicated that plant height was not a major determinant of yield under phosphorus fertilization, whereas biomass and pod number were strongly correlated with yield [29]. These findings agree with the present study, demonstrating that plant height is not a reliable predictor of yield performance in common bean under intercropping.

Branches per Plant, Pods per Plant, and Seeds per Pod: Research based recommended intercropping system as the best practice because of its significantly increased branching (3.85 vs. 3.13), pods per plant (9.58 vs. 7.31), and seeds per pod (3.94 vs. 3.44) of haricot bean as compared to farmers practiced (Table 2). These components are critical determinants of yield, as each additional branch provides sites for flowering and pod initiation. Some Published studies strongly support this finding. Haricot bean grain yield was strongly linked to pods per plant and seeds per pod, with branching pattern being a major physiological driver [30]. Optimized spatial arrangement increased branching and pod formation due to reduced shading and competition in an intercropping system with maize [31]. Improved spacing increased the number of reproductive nodes and ultimately pods per plant [32]. Thus, the enhanced branching and pod set under RBIP likely result from better access to light, nutrients, and moisture due to improved spatial geometry, supporting more effective reproductive development.

Biomass Yield: Biomass yield of haricot bean was significantly higher under RBIP (3,971.7 kg/ha) than FPIP (2,825.0 kg/ha) (Table 2). Increased vegetative growth under RBIP indicates superior resource utilization efficiency and reduced interspecific and intraspecific competition.

Comparable studies also observed that biomass accumulation increases under optimized intercropping patterns. In Bako, Ethiopia, [33] found that improved row arrangement in bean cereal intercropping increased dry matter accumulation by enhancing light interception. [29] reported that biomass yield of common bean responded strongly to improved fertility and spacing, which reduced competition for soil nutrients. Since biomass is strongly associated with the production of photosynthates required for pod formation and seed filling, its increase under research based recommended intercropping system supports the higher grain yield observed.

Grain Yield: Haricot bean grain yield increased by approximately 48.6% under research-based recommender intercropping system compared with farmers practiced (1,845.7 vs. 1,242.2 kg/ha) (Table 2). This substantial improvement reflects the cumulative influence of enhanced branching, pod formation, seed development, and biomass production.

Yield gaps between intercropping arrangements have been widely documented. [31] reported up to 55% yield improvement in haricot bean under optimized maize-bean intercropping compared with farmer practices. In Hosanna, [34] also found that research-recommended intercropping patterns increased bean grain yield by 40-60% through enhanced photosynthetic efficiency. Inappropriate intercropping arrangements can reduce common bean yield because of shading and competition for resources [35, 36]. The present study aligns with research suggesting that intercropping is beneficial only when planting geometry is properly optimized. Research based recommended intercropping system evidently allowed better resource partitioning, leading to more effective assimilating production and distribution to pods and seeds.

Table 2. Yields and yield related parameters of haricot bean as affected by the treatments.

Trt	pH (cm)	BPP (No)	NPPP (No)	NSPP (No)	BM (kg/ha)	GY (kg/ha)
FPI	37.07	3.13b	7.31b	3.44b	2825.00b	1242.21b
RBI	38.38	3.85a	9.58a	3.94a	3971.70a	1845.70a
Mean	37.72	3.49	7.94	3.74	2898.34	1347.65
PV	NS	**	**	**	***	***
LSD (0.5%)	8.74	0.65	2.14	0.461	598.95	234.83
CV (%)	23.19	18.57	29.21	12.32	20.68	17.43

Where FPIP = farmers practiced intercropping pattern; RBIP = research based intercropping pattern; Sig = significance; LSD = least significant difference; CV = Coefficient of variation; PH = plant height; BPP = branches per plant; NS = Not significant, NPPP = numbers of pods per plant; NSPP = numbers of seeds per pod; BM= biomass yield and GY = grain yield

3.4. Partial Budget Analysis

The partial budget analysis demonstrated that intercropping haricot beans with maize is more profitable than sole cropping. The Research-Based Intercropping Pattern (RBIP) produced the higher net benefit (187,081 ETB/ha) (Table 3). Farmers practiced intercropping system also improved profitability compared to sole cropping but remained lower than the recommended system search based. The marginal rate of return (MRR) further confirmed economic superiority the Farmers practiced intercropping achieved 378.11%, while the research-based intercropping achieved a very high 725.63%. Since MRR values above 100% meet recommended economic thresholds, both intercropping practices are profitable; however, the research based intercropping system is clearly the most economically efficient option. These results confirm that properly designed intercropping systems enhance total productivity, income, and resource-use efficiency, making a superior agronomic and financial choice for farmers.

Table 3. Partial budget analysis.

Trt	BGY (qt/ha)	ABGY (qt/ha)	MGY (qt/ha	AMGY (qt/ha)	TGFB (ETB/ha)	TVC (birr/ha)	NB (birr/ha)	MRR (%)
Sole	0	0	54.56	49.10	171864.00	58952.00	112912.00	
FPI	12.42	11.178	51.39	46.25	228946.50	70891.00	158055.50	378.11
RBI	18.46	16.614	51.52	46.37	261972.00	74891.00	187081.00	725.63

Where Sole = sole maize planting, FPIP = farmers practiced intercropping pattern; RBIP = research based intercropping pattern; BGY = Bean grain yield; ABGY = Adjusted bean grain yield; MGY = maize grain yield; AMGY = Adjusted maize grain yield; qt/ha = Quintal per hectare; TGFB = Total gross field benefit; TVC =Total variable cost; NB = Net benefit and MRR = Marginal rate of return. While the unit price of maize and haricot bean at farm gate during harvesting time, urea and NPS during the planting time were 35, 60, 42 and 40 birr/kg respectively.

3.5. Potential for Scaling Up the Technology in Other Regions of Ethiopia

The results of this study demonstrate that maize-haricot bean intercropping improved crop productivity and soil fertility compared with sole cropping systems. Given the similar agro-ecological conditions in many parts of Ethiopia, particularly in the western, southwestern, and central highlands, the tested intercropping arrangements could be successfully adapted in other regions with comparable rainfall patterns, soil types, and farming systems. The integration of legumes such as haricot bean with maize can enhance resource use efficiency, improve soil fertility through biological nitrogen fixation, and increase farmers' income by producing two crops from the same field.

Scaling up this technology may therefore contribute to sustainable crop production and improved soil health in smallholder farming systems. However, successful dissemination requires farmer training, availability of improved seed varieties, and location-specific agronomic recommendations. Further multi-location trials are recommended to validate the performance of the intercropping system under diverse agro-ecological conditions in Ethiopia.

4. Conclusion and Recommendation

Research-Based Intercropping Pattern (RBIP) improved nearly all soil chemical properties compared to before planting, sole cropping, and farmers' practice. Soil pH increased by about 9.3%. It also increased organic carbon (26.3%), total nitrogen (23.8%), and available phosphorus (10.3%), while reducing exchangeable acidity (-69.7%), indicating strong soil restoration potential. Sole maize showed the lowest soil fertility improvement, highlighting the limitation of continuous monocropping.

All maize parameters showed no significant differences ($P > 0.05$) among treatments. Sole maize slightly outperformed intercropping in numeric grain yield, but not significantly. Research-based intercropping maintained maize productivity close to sole cropping, confirming that optimized spacing minimizes competition.

All traits of haricot bean except plant height differed significantly between treatments. Research based recommended intercropping system increased branches per plant, pods per plant, seeds per pod, biomass yield and grain yield by about 23, 31, 14, 40.6 and 48.6% respectively. Farmers practiced intercropping system produced lower bean yield. Also, from the former experiments of the study during technology generation, the recommended intercropping system resulted higher LER (1.58) and *LEC* (*0.63*) indicating that the tested spatial and temporal arrangement improved biological efficiency of the land use. Both intercropping systems increased profitability compared to sole maize net benefits*;* Sole maize (112,912 ETB ha^{-1}), local practice (158,055.5 ETB ha^{-1}) and recommended (187,081 ETB ha^{-1}). With accepTable MRR. Therefore, research based findings on maize haricot bean intercropping system should be recommended for farmers in the study area and similar agroecology because it optimizes space, reduces competition, and increases overall productivity. Demonstration plots should be established to show farmers the benefits of optimized intercropping.

Abbreviations

ANOVA	Analysis of Variance
BM	Biomass Yield
CN	Cob Number
CV	Coefficient of Variation
CW	Cob Weight
ETB	Ethiopian Birr
FAO	Food and Agriculture Organization
FPIP	Farmers Practiced Intercropping Pattern
GY	Grain Yield
HI	Harvest Index
LEC	Land Equivalence Coefficient
LER	Land Equivalence Ratio
LSD	Least Significant Difference
MRR	Marginal Rate of Return
PP	Plant Population
RBIP	Research Based Intercropping Pattern
RCBD	Randomized Complete Block Design

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Author Contributions

Temesgen Chimdessa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing

Chaltu Regasa: Data curation, Investigation, Methodology, Writing – review & editing

Mintesinot Desalegn: Data curation, Investigation, Methodology, Writing – review & editing

Chalsissa Takale: Methodology, Project administration, Supervision, Validation, Writing – review & editing

Naferom Negesa: Data curation, Methodology, Supervision, Writing – review & editing

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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