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Biofertilisers and Micronutrients Enhance Productivity and Land-Use Efficiency of Cereal-Legume Intercropping Systems on Indonesian Drylands

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ABSTRACT

Low soil fertility and limited availability of nutrients negatively affect the productivity and sustainability of tropical dryland agriculture. Cereal-legume intercropping can improve land use efficiency. However, the effectiveness of cereal-legume intercropping in nutrient-limited drylands is dependent on appropriate nutrient management. This study examined the effects of an integrated biofertiliser-micronutrient package on crop production, land use efficiency, cropping system productivity and economic performance of cereal-based intercropping systems in Indonesian drylands. The research was conducted in Garut, West Java, Indonesia, during October 2022-March 2023. The research used a split-plot randomised complete block design with four replications. Three intercropping systems, maize-upland rice, maize-soybean and upland rice-soybean, were the major plots. The subplots consisted of two nutrient management regimes: (P_0) locally advised fertilisation and (P_1) recommended fertilisation + biofertiliser at 5 L ha^{-1} + micronutrient fertiliser at 10 kg ha^{-1}. Organic manure (7.5 t ha^{-1}) and dolomite (1.5 t ha^{-1}) were uniformly applied to all plots. The integrated treatment improved crop growth and productivity, with responses varying among intercropping systems. Upland rice-soybean under integrated nutrient management achieved the highest Land Equivalent Ratio (LER; 1.56) and Cropping System Efficiency (CSE; 1.50), while farmers' income increased

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by up to 81.72%. The novelty of this study lies in the field evaluation of an integrated biofertiliser-micronutrient package in different cereal-legume intercropping systems in the tropical dryland environments of Indonesia, correlating agronomic performance with land-use efficiency and economic returns. The findings demonstrate the potential of integrated biological and micronutrient management to support sustainable intensification of dryland farming.

Keywords: Agroecosystem, crop production, land equivalent ratio, mineral nutrition, plant growth-promoting microorganisms

INTRODUCTION

Dryland agriculture plays an important role in supporting food security and rural livelihoods in tropical regions, including Indonesia. The conversion of productive paddy fields to non-agricultural uses has reduced the area available for rice, maize, and soybean production, increasing the importance of drylands as an alternative resource for food-crop production (Mulyani, 2016). Indonesia has approximately 70 million ha of dryland resources (BPS, 2022; Pusat Data dan Sistem Informasi Pertanian [Pusdatin], 2021), providing considerable potential for agricultural intensification. However, the productivity of these lands remains constrained by low soil fertility, limited availability of macro- and micronutrients, low organic matter, erratic rainfall, and rapid nutrient depletion (Srinivasarao et al., 2023). In many dryland soils, low soil organic carbon and weak biological activity reduce nutrient retention and may limit the efficiency of conventional fertiliser inputs.

Cereal-legume intercropping is widely recognised as a sustainable intensification strategy for improving resource-use efficiency and land productivity in rainfed and dryland environments. Intercropping cereals such as maize and upland rice with legumes such as soybean or mungbean allows complementary use of light, water, space, and nutrients, while legumes may contribute biologically fixed nitrogen to the cropping system (Jensen et al., 2020; Omara et al., 2019; Peoples et al., 2022). The resulting complementarity can provide a land-use advantage over monocropping, commonly expressed by a Land Equivalent Ratio (LER) greater than one. However, the productivity advantage of cereal-legume intercropping is strongly influenced by soil fertility and nutrient management, particularly where soil nutrient availability and biological activity are low (Agsari et al., 2020; Kristiono et al., 2020). Thus, the biological complementarity between cereals and legumes does not necessarily translate into consistently high productivity under nutrient-constrained dryland conditions. Similar advantages of cereal-legume intercropping have been documented globally (Agbor et al., 2023; Latati et al., 2019; Pierre et al., 2022).

Inorganic fertilisers remain the major source of nutrients in many dryland production systems. However, inappropriate or imbalanced fertiliser use may contribute to declining soil quality, reduced nutrient-use efficiency, and deterioration of soil biological processes

(Krasilnikov et al., 2022; Titirmare et al., 2023; Wang et al., 2021). Excessive mineral fertiliser inputs may also negatively affect beneficial soil microorganisms, including mycorrhizal associations that contribute to nutrient acquisition and soil aggregation (Rillig et al., 2019). Complementary sources of nutrients are therefore increasingly important in sustainable agricultural intensification, especially when they can enhance nutrient availability and support biological activities in the soil.

Biofertilisers containing beneficial microorganisms such as *Azospirillum*, *Rhizobium*, and phosphate-solubilising bacteria can help make nutrients available to plants, stimulate root growth, and improve nutrient uptake (Mahanty et al., 2017; Soumare et al., 2020). Micronutrients such as zinc (Zn), boron (B) and iron (Fe) are also crucial for optimal plant growth and development as they participate in different physiological processes, including enzyme function, photosynthesis, reproductive development and grain formation. Therefore, combining biological nutrient inputs with micronutrients may provide a complementary nutrient-management strategy for crops grown under nutrient-constrained conditions. Nevertheless, previous studies have predominantly examined biofertilisers as individual inputs or in relation to particular cereal-legume combinations. For example, biofertiliser application has been shown to improve productivity and LER in maize-soybean intercropping systems (Ünay et al., 2021), while recent field research has further demonstrated positive effects of biofertilisers on land-use efficiency across cereal-legume mixtures (Pérez-Bernal et al., 2025). These findings establish the potential of biofertilisers but also indicate that the use of biofertiliser alone is not, in itself, a sufficient basis for claiming novelty.

The remaining knowledge gap concerns whether an integrated nutrient package combining biofertiliser and micronutrients with recommended mineral fertilisation can consistently improve cereal-legume intercropping performance under nutrient-constrained tropical dryland conditions. In particular, field-based evidence comparing the response of different cereal-legume combinations to such an integrated nutrient package in Indonesian drylands remains limited. Moreover, studies often focus on individual crop yield or LER, whereas a simultaneous evaluation of crop productivity, land-use efficiency, cropping-system efficiency, and economic returns can provide a more comprehensive assessment of the technology's practical value. This is important because an agronomically superior intercropping system is more likely to be adopted when its land-use advantage is accompanied by tangible economic benefits to farmers. Recent research has demonstrated that cereal-legume intercropping can provide economic advantages under variable rainfall conditions, highlighting the importance of integrating agronomic and economic assessments when evaluating dryland intensification strategies.

Therefore, the novelty of the present study is not the use of biofertiliser, micronutrients, or cereal-legume intercropping individually, all of which have been investigated

previously. Rather, the novelty lies in field-testing an integrated biofertiliser-micronutrient nutrient package, applied in addition to recommended fertilisation, across cereal-legume intercropping systems under Indonesian tropical dryland conditions and linking its effects on crop productivity with land-use efficiency and economic performance. This approach provides a system-level assessment of whether biological and micronutrient supplementation can strengthen the productivity advantage of cereal-legume intercropping in nutrient-constrained drylands.

Accordingly, this study aimed to evaluate the effects of supplementing recommended fertilisation with biofertiliser and micronutrients on crop growth, yield, land-use efficiency, cropping-system efficiency, and economic returns of cereal-legume intercropping systems in Indonesian drylands. The experiment compared two nutrient-management regimes: (1) recommended fertilisation and (2) recommended fertilisation supplemented with biofertiliser at 5 L ha^{-1} and micronutrients at 10 kg ha^{-1}, with organic manure at 7.5 t ha^{-1} and dolomite at 1.5 t ha^{-1} uniformly applied to all treatments. The study was designed to provide field-based evidence for an integrated nutrient management strategy that improves the productivity and resource-use efficiency of cereal-legume systems while enhancing their economic attractiveness to dryland farmers.

MATERIALS AND METHODS

Study Area and Experimental Materials

The field experiment was conducted in Pangeureunan Village, Balubur Limbangan District, Garut Regency, West Java Province, Indonesia (7°00′11″ S, 107°56′53″ E), during one cropping season from October 2022 to March 2023. The experimental site was located at approximately 600 m above sea level and had a tropical humid climate, with an average annual rainfall of approximately 2,075 mm and a mean annual temperature of approximately 20 °C. The soil was classified as Cambisols. The site had a medium-to-fine soil texture, good drainage, and hilly topography (Central Statistics Agency of Garut Regency. 2022). Before the experiment, the field had been used for a maize-tobacco rotation.

Before land preparation, composite soil samples were collected from the experimental area at a depth of 0-20 cm to characterise the initial soil condition. The initial soil analysis included [pH, organic C, total N, available P, exchangeable K, and other parameters actually measured in the study]. The results were used to characterise the nutrient status of the experimental site and to support the interpretation of the response to the nutrient-management treatments.

The evaluated crops were maize (*Zea mays* L.) cv. NASA 29, upland rice (*Oryza sativa* L.) cv. Inpago 11 and soybean (*Glycine max* L.) cv. Anjasmoro. Soil additions employed were organic fertiliser (manure) and dolomite. Inorganic fertilisers utilised were urea and NPK compound fertiliser; urea included 46% N, and NPK fertiliser contained 15% N,

10% P_2O_5 and 12% K_2O. The biofertiliser utilised in this experiment was *Bacillus* sp. (viable cell density > 1.0 × 10 6 CFU mL^{-1}), *Ochrobactrum sp*. (viable cell density > 1.0 × 10 5 CFU mL^{-1}) and *Alcaligenes* sp. (viable cell density > 1.0 × 10 5 CFU mL^{-1}). The micronutrient fertiliser was composed of 17% Zn, 3% Cu, 0.7% B, 0.6% Mn and 0.01% Mo.

Experimental Design and Treatments

The experiment employed a split-plot randomised complete block design (RCBD) with four replications. The experiment was established on approximately 1.5 ha of a farmer's field.

The main-plot factor was the cropping system, consisting of three cereal-legume or cereal-cereal intercropping systems:

a) **MR**: maize-upland rice;
b) **MS**: maize-soybean; and
c) **RS**: upland rice-soybean.

The subplot factor was nutrient management, consisting of two treatments:

a) **P_0:** locally recommended fertilisation (control); and
b) **P_1:** locally recommended fertilisation + biofertiliser + micronutrient fertiliser.

Thus, the experiment consisted of six treatment combinations (3 cropping systems × 2 nutrient-management treatments), with four replications, giving a total of 24 experimental units. Each experimental unit covered an area of 500 m².

The application rates for inorganic fertilisers (urea and compound NPK), biofertilisers, and micronutrient fertilisers were determined based on established recommendations for each crop and local farmers' production practices (Table 1).

Table 1
Intercropping arrangements and plant densities

Main Plot Treatments Code	Crop	Rows	Row Spacing (cm)	In-row Spacing (cm)	Population (plants ha-1)
MR	Maize	2	60	25	26,667
	Upland Rice	9	20	15	199,800
MS	Maize	2	60	25	24,000
	Soybean	7	30	15	142,222
RS	Upland Rice	9	20	15	183,333
	Soybean	5	30	15	100,000

Cropping System Arrangement

Planting appeared in the cropping patterns presented in Table 2. The population and spatial arrangement of plants were maintained consistent with the existing intercropping system to ensure the relative contribution of each crop component could be compared across systems.

Table 2
Fertiliser treatment details

Subplot Treatments Code	Crop	Inorganic Fertiliser	Biofertiliser (l ha-1)	Micronutrient (kg ha-1)
P0	Maize	Recommended Dosage	-	-
	Upland Rice	Recommended Dosage	-	-
	Soybean	Recommended Dosage	-	-
P1	Maize	Recommended Dosage	5	10
	Upland Rice	Recommended Dosage	5	10
	Soybean	Recommended Dosage	5	10

Note. Recommended inorganic fertilisers dosage (Maize = 150 kg/ha, upland rice = 100 kg/ha, and soybean = 50 kg/ha)

Monoculture crop yields used to calculate LER and CSE were obtained from farmers' fields near the experimental site, using management practices identical to those used in the experiment.

All treatments were uniformly managed using standard crop management procedures. Weeds were treated manually, and pests and diseases were controlled by locally recommended procedures. The crops were mainly rain-fed, with additional irrigation being used when necessary to prevent excessive water stress.

Application of Fertilisers and Biofertilisers

Soil amendments were organic fertiliser (manure) at 7.5 t ha^{-1} and dolomite at 1.5 t ha^{-1}. These components were evenly distributed to all experimental plots before planting. Inorganic fertilisers, Urea, compound NPK and micronutrients were treated in two doses at 10 days after planting (DAP) and 30 DAP. One-third of the dose was applied at 10 DAP and two-thirds at 30 DAP. The biofertiliser was applied 3 times at 7, 14, and 28 days after planting (DAP) by spraying the product onto the soil at a 1:60 ratio.

DATA COLLECTION

Data was collected through direct field observations and measurements at specific periods of crop growth.

Growth Parameters

Growth data were recorded at 2, 4, 6 and 8 weeks after planting (WAP). The variables measured were: (1) plant height (cm) of maize, upland rice and soybean; (2) stem diameter (mm) of maize; (3) number of tillers per $plant^{-1}$ of upland rice and (4) number of branches per $plant^{-1}$ of soybean.

Measurements were conducted on the representative plants within each plot, selected from the specified sampling area (excluding border plants). Repeated measurements were taken from the same plants if possible.

Crop Yield and Yield Components

Yield components and grain yield were measured at physiological maturity for each component crop. For maize, the measures were cob length, cob diameter, 100-grain weight, and grain yield. For upland rice, measurements included panicle length, number of filled grains per panicle^{-1}, 1,000-grain weight, and grain yield. For soybean, measurements included the number of filled pods per plant^{-1}, the number of unfilled pods per plant^{-1}, 100-grain weight, and grain yield.

Grain yield was determined from the harvested net plot area and converted to t ha^{-1} at the appropriate standard moisture content of 14% for upland rice and 12% for maize and soybean.

Land-Use Efficiency

Land-use efficiency is an important indicator for assessing the productivity advantage of intercropping relative to monocropping. In intercropping systems, land-use efficiency is commonly quantified using the Land Equivalent Ratio (LER), which represents the amount of land required under monocropping to produce the same yields obtained from one unit of land under intercropping (Khanal et al., 2021). LER is calculated using the formula as in Equation 1:

$$LER = \sum_{i=1}^{n} \frac{Xi}{Yi} \quad [1]$$

where:
X_i = yield of crop *i* (t ha^{-1}) in the intercropping system
Y_i = yield of crop *i* (t ha^{-1}) in monoculture

An LER > 1 indicates that intercropping uses land more efficiently than the corresponding monocropping systems, whereas LER = 1 indicates no land-use advantage and LER < 1 indicates a land-use disadvantage.

Cropping System Efficiency

Cropping System Efficiency (CSE) is an index used to evaluate the overall efficiency of an intercropping system by considering the combined yield of component crops relative to their corresponding monocultures and adjusting this productivity advantage according

to the duration of the cropping system (Dariush et al., 2006). Cropping System Efficiency (CSE) was calculated to assess the combined biological and temporal efficiency of the intercropping system as in Equation 2:

$$CSE = (Yia + Yib) / (Yma + Ymb) \times (ta + tb)/T \quad [2]$$

where:
Yia = yield of crop A in intercropping (t ha^{-1})
Yib = yield of crop B in intercropping (t ha^{-1})
Yma = yield of crop A in monocropping (t ha^{-1})
Ymb = yield of crop B in monocropping (t ha^{-1})
ta, tb = duration of monocropping for crop A and B (days)
T = total duration of intercropping (days)

A CSE value greater than 1 indicates an overall efficiency advantage of the intercropping system relative to the corresponding monocropping systems under the conditions of the experiment.

Economic Analysis

Economic performance was assessed using production costs, gross revenue, and the revenue-to-cost ratio (R/C ratio).

Production costs included seed, mineral fertilisers, biofertiliser, micronutrient fertiliser, organic manure, dolomite, labour, and other production inputs, which differed among treatments. The cost of each input was based on the prevailing local prices during the 2022-2023 cropping season. Gross revenue is calculated by multiplying crop yield (kg ha^{-1}) by the local farm-gate selling price (US$ kg^{-1}).

The revenue-to-cost ratio was calculated as (Beding, 2023) in Equation 3:

$$RC\ ratio\ = \frac{TR}{TC} \quad [3]$$

where:
TR = total revenue
TC = total production cost.

An R/C ratio > 1 indicates that the farming system generates revenue greater than its production cost.

For intercropping systems, total revenue was calculated from the combined value of all component crops harvested from the same land area.

Statistical Analysis

The experimental data were analysed according to the split-plot RCBD model, with cropping system as the main-plot factor and nutrient management as the subplot factor.

Analysis of variance (ANOVA) was conducted to test the main effects of cropping system and nutrient management and their interaction. The Least Significant Difference (LSD) test was used to differentiate significant differences at the 5% significance level. The statistical analysis was performed with SPSS version 25.

The interaction between cropping system and nutrient management was considered particularly important because it determined whether the response to the integrated biofertiliser-micronutrient treatment was consistent among maize-upland rice, maize-soybean, and upland rice-soybean intercropping systems.

RESULTS AND DISCUSSION

Site Description

A pre-experimental soil analysis was conducted to determine the soil's chemical and physical properties (Table 3).

The research site was characterised by acidic soils (pH < 4.5) with low available potassium (K_2O) and high phosphorus (P_2O_5) content that remains largely unavailable due to fixation. The soil texture was classified as silty clay. Acidic soils are prone to potassium leaching (Widowati et al., 2012) and aluminum (Al) saturation, which inhibits nutrient uptake. Furthermore, micronutrient deficiencies, particularly magnesium (Mg), are common under such conditions. Soil amendments, including lime and organic matter, are essential

Table 3
Physical and chemical properties of the experimental soil

Parameter	Unit	Value	Category
Chemical Properties			
pH (H_2O)	-	4.50	Acidic
pH (KCl)	-	3.90	Acidic
Organic carbon (C-organic)	%	2.01	Low
Total nitrogen (N-total)	%	0.15	Low
C/N ratio	-	13.00	-
P_2O_5	Mg 100g-1	58.00	High
K_2O	Mg 100g-1	25.90	Moderate
Available phosphorus (P)	Mg kg-1	11.58	High
Physical Properties			
Sand	%	23.00	-
Silt	%	30.00	-
Clay	%	47.00	Silty clay

for enhancing soil pH and organic carbon content, while micronutrient fertilisers restore trace-element availability.

Biofertilisers contribute to nutrient solubilisation, particularly phosphorus, by releasing P bound in the soil matrix. Their application improved plant height and growth parameters, particularly after eight weeks of planting, consistent with the time needed for microbial populations to establish under low-pH conditions. Rohmah et al. (2016) reported that nitrogen-fixing bacteria, such as Rhizobium, require a pH > 6 to proliferate and function effectively, as well as a carbon source derived from decomposed organic matter.

Crop Growth Response to Integrated Nutrient Management

Visual field observations indicated a good adaptation of all three crop species to closer spacing in the intercropping systems. Dryland conditions were characterised by vigorous vegetative development in upland rice (*Oryza sativa* var. Inpago 11), consistent with its tolerance to moderate shade. Maize (*Zea mays* var. NASA 29) produced robust stalks and, in many instances, two ear shoots per plant, showing early reproductive potential. The soybean (*Glycine max* var. Anjasmoro) showed uniform vegetative growth and was somewhat taller when intercropped with maize than with upland rice, indicating moderate etiolation due to partial light competition (Figure 1).

The ANOVA findings (Table 4) revealed no significant differences among the three intercropping combinations (maize-upland rice, maize-soybean, and upland rice-soybean) for most early vegetative attributes at 2-4 WAP. This means that the higher plant density did not generate crucial competition for light, as canopy light intensity was above 50%, and Padang et al. (2020) stated that this was sufficient for optimal upland rice growth. Only at lower light threshold values were substantial reductions in growth rate observed, confirming that evaluated planting configurations did not cause severe shading stress (Xu et al., 2024).



maize–upland rice intercropping (MR) | maize–soybean intercropping (MS) | Upland rice–soybean intercropping (MS)

Figure 1. Vegetative performance of maize-upland rice, maize-soybean, and upland rice-soybean intercropping under biofertiliser and micronutrient application

Table 4
ANOVA results for plant height and growth components of maize, upland rice, and soybean in intercropping systems with biofertiliser and micronutrient application

Parameter	Source of Variation	2 WAP		4 WAP		6 WAP		8 WAP	
		sig.	CV (%)	sig.	CV (%)	sig.	CV (%)	sig.	CV (%)
Plant height of maize	Intercropping system (T)	ns	4.95	ns	1.64	ns	1.45	ns	1.58
	Fertilisation (P)	ns	25.76	ns	2.38	ns	7.39	*	5.49
	Interaction (T×P)	ns		ns		ns		ns	
Plant height of upland rice	Intercropping system (T)	ns	5.63	ns	7.98	ns	3.65	ns	1.92
	Fertilisation (P)	ns	13.82	ns	20.51	ns	6.78	*	8.37
	Interaction (T×P)	ns		ns		ns		ns	
Plant height of soybean	Intercropping system (T)	ns	3.82	ns	5.61	*	2.31	*	2.25
	Fertilisation (P)	ns	7.69	ns	24.61	ns	10.61	**	3.13
	Interaction (T×P)	ns		ns		ns		ns	
Stem diameter maize	Intercropping system (T)	ns	24.73	ns	7.39	ns	5.95	ns	1.95
	Fertilisation (P)	ns	11.68	ns	1.15	ns	0.88	ns	9.79
	Interaction (T×P)	ns		ns		ns		ns	
Number of tillers of upland rice	Intercropping system (T)	ns	6.71	ns	6.38	ns	7.38	ns	4.91
	Fertilisation (P)	ns	5.45	ns	7.62	*	8.29	*	9.17
	Interaction (T×P)	ns		ns		ns		ns	
Number of branches soybean	Intercropping system (T)	ns	5.08	ns	2.81	ns	3.51	ns	7.46
	Fertilisation (P)	ns	6.15	ns	9.87	*	1.90	*	19.79
	Interaction (T×P)	ns		ns		ns		ns	

Note. * = significantly different at $p < 0.05$; ** = significantly different at $p < 0.01$; ns = not significant

The application of biofertiliser combined with micronutrients (P_1) significantly increased plant height in maize, upland rice, and soybean at 8 WAP, along with greater tiller production in upland rice and more branches in soybean from 6 WAP onwards (Tables 4 and 5). These responses can be explained by the enhancement of nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K), mediated by biofertiliser components such as phosphate-solubilising bacteria (PSB), potassium-solubilising bacteria (KSB), and nitrogen-fixing microorganisms. The inclusion of phytohormone-producing microbes in biofertilisers that synthesise gibberellins, indole-3-acetic acid (IAA), and cytokinins likely promoted cell elongation, tiller initiation, and lateral branching (Asra & Samarlina, 2020).

The most significant plant reaction of soybean to P_1 may be connected to its ability to fix nitrogen from the air in symbiosis with *Bradyrhizobium japonicum* (Bhat et al., 2015). The symbiotic association may meet the nitrogen requirements of soybean and may also contribute to the nitrogen availability in the surrounding rhizosphere by root exudates and other rhizosphere processes (Yatsenko et al., 2023). The presence of micronutrients,

Table 5
LSD test results for the average plant height, corn stem diameter, number of upland rice tillers, and number of soybean branches influenced by the application of biofertiliser and micronutrients in intercropping systems

Fertilisers	Plant Type	Plant Height		Stem Diameter Maize	
Maize Crop		6 WAP	8 WAP	6 WAP	8 WAP
P_0	MR	175.40a	209.95a	3.15a	3.36a
	MS	172.93a	211.13a	3.37a	3.39a
P_1	MR	179.15a	220.80b	3.51a	3.60a
	MS	179.60a	225.07b	3.68a	3.69a
Fertilisers	**Plant Type**	**Plant Height**		**Number of Tillers Upland Rice**	
Upland Rice Crop		**6 WAP**	**8 WAP**	**6 WAP**	**8 WAP**
P_0	MR	77.67	102.73a	12.53a	14.30a
	RS	76.73	100.00a	11.00a	13.87a
P_1	MR	76.70	107.53b	14.03b	17.20b
	RS	75.40	106.87b	12.93a	16.83b
Fertilisers	**Plant Type**	**Plant Height**		**Number of Branches of Soybean**	
Soybean Crop		**6 WAP**	**8 WAP**	**6 WAP**	**8 WAP**
P_0	MS	73.90	98.62a	8.67a	13.28a
	RS	70.80	102.90a	8.13a	12.30a
P_1	MS	77.10	109.68b	10.97b	16.30a
	RS	74.45	114.48b	10.87b	17.85b

Note. Means followed by the same letter within a column are not significantly different according to the LSD test at $p < 0.05$

especially Zn and Cu, in P1 might have also played a role in promoting plant growth, as these elements participate in several physiological processes such as enzyme activity, chlorophyll synthesis and nucleic acid metabolism (Fauziah et al., 2018). Effects of P_1 on early vegetative development were less noticeable in maize and highland rice. However, an appropriate supply of micronutrients is necessary to maintain photosynthetic activity and to enable subsequent reproductive growth.

Vegetative increases under P_1 definitely extended into the reproductive period. Improved stem vigour and leaf area of maize resulted in more effective assimilate transport to the growing ear. Increased availability of P and K is known to promote cob initiation, kernel set and grain filling (Ndor et al., 2016). In upland rice, an increase in the tiller number at the end of the vegetative phase enhanced the productive panicles per plant, which is one of the primary components of grain output (Kalaitzidis et al., 2025).

In soybeans, better vegetative response (especially increased branching) resulted in increased reproductive nodes and hence increased pod set. Micronutrients like molybdenum (Mo) and Zn are of special importance for the reproductive performance of soybean as they promote nodulation efficiency, nitrogenase activity and seed filling processes (Fageria &

Oliveira, 2014). This explains the substantially increased seed weight of soybean under P_1 as compared to maize and upland rice, indicating its higher nutritional need and sensitivity.

Crop Yield Response to Integrated Nutrient Management

During the generative phase, all crop species developed vigorously in the generative phase throughout the treatments (Figure 2). Inpago 11 upland rice yielded grains that were well-filled, despite its characteristically short panicles. Approximately 80% of the maize (NASA 29) plants formed two large cobs, and Anjasmoro soybeans produced numerous, well-filled pods in all intercropping systems. Maize cobs were bigger, rice panicles were longer, and soybean pods were more abundant in biofertiliser-treated plots, showing more visual variations.

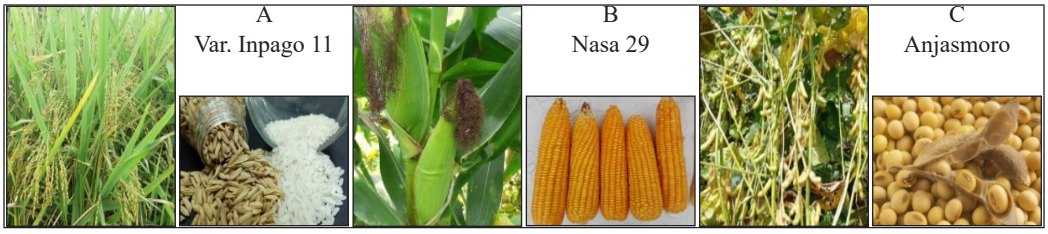

Figure 2. Plant performance during the generative phase of upland rice (A), maize (B), and soybean (C) in intercropping systems with biofertiliser and micronutrient application on dryland

ANOVA results (Table 6) indicated that biofertiliser and micronutrient application significantly improved cob diameter, cob length, 100-grain weight, and maize productivity, with the strongest effects observed in the maize-soybean (MS) intercropping system. In upland rice, both the intercropping system and fertilisation significantly influenced panicle length, number of grains per panicle, and productivity, with the rice-soybean (RS) combination under enhanced fertilisation showing the greatest gains. For soybeans, fertilisation significantly increased the number of filled pods in both MS and RS systems, while reducing the number of empty pods in the RS system. No significant interaction effects between the intercropping system and fertilisation were detected for any crop.

The LSD comparisons showed that the addition of biofertiliser and micronutrients (P_1) improved several yield components and crop productivity, although the magnitude of the response varied among crops and intercropping systems (Table 7). In maize, the clearest response occurred in the maize-soybean (MS) system. Compared with P_0, P_1 increased cob length from 18.17 to 20.55 cm (13.1%), cob diameter from 4.70 to 5.93 mm (26.2%), 100-grain weight from 26.89 to 29.75 g (10.6%), and grain productivity from 5.72 to 6.86 t ha^{-1} (19.9%). The different letters in the LSD test indicate that these values were significantly higher under P_1 in the MS system. In contrast, the maize-upland rice (MR) system showed smaller numerical increases, and the corresponding means shared the same

Table 6
ANOVA results for yield components and productivity of maize, upland rice, and soybean in intercropping systems with biofertiliser and micronutrient application

Crops	Source of Variation	Cob Diameter (Maize)		Cob Length		Weight 100 Grains		Productivity	
		sig.	CV (%)	sig.	CV (%)	sig.	CV (%)	sig.	CV (%)
Maize	Intercropping system (T)	ns	4.23	ns	9.71	ns	7.01	ns	3.08
	Fertilisation (P)	*	10.26	*	7.26	*	5.17	*	1.73
	Interaction (T×P)	ns		ns		ns		ns	
		Length Panicles		**Number of Grains per Panicle**		**Weight 1000 Grains**		**Productivity**	
Upland rice	Intercropping system (T)	*	4.41	*	1.13	ns	2.86	*	4.82
	Fertilisation (P)	*	10.37	*	13.83	ns	13.73	*	1.97
	Interaction (T×P)	ns		ns		ns		ns	
		Number of Filled Pods		**Number of Empty Pods**		**Weight 1000 Grains**		**Productivity**	
Soybean	Intercropping system (T)	ns	4.04	ns	6.08	ns	2.86	ns	4.82
	Fertilisation (P)	*	17.57	*	7.57	ns	13.73	*	1.97
	Interaction (T×P)	ns		ns		ns		ns	

Note. * = significantly different at $p < 0.05$; ns = not significant

Table 7
SD test results for yield components and productivity of maize, upland rice, and soybean in intercropping systems with biofertiliser and micronutrient application

Fertilisers	Plant Type	Maize			
		Cob Diameter (mm)	Cob Length (cm)	Weight 100 Grains (g)	Productivity (t ha-1)
P_0	MR	4.80a	17.50a	27.30a	5.80a
	MS	4.70a	18.17a	26.89a	5.72a
P_1	MR	5.57a	19.80a	27.70a	6.30a
	MS	5.93b	20.55b	29.75b	6.86b
Fertilisers	**Plant Type**	**Upland Rice**			
		Length Panicles (cm)	Number of Grains per Panicles	Weight 1000 Grains (g)	Productivity (t ha-1)
P_0	MR	21.10a	190.50a	23.50a	3.97a
	RS	23.40a	197.50a	24.60a	4.01a
P_1	MR	24.23a	200.00a	23.90a	4.23a
	RS	25.78b	205.00a	24.80a	5.20b
Fertilisers	**Plant Type**	**Soybean**			
		Number of Filled Pods	Number of Empty Pods	Weight 100 Grains (g)	Productivity (t ha-1)
P_0	MS	68.00a	11.70a	18.33a	1.94a
	RS	66.10a	11.20a	18.00a	1.70a
P_1	MS	75.20b	12.20a	19.30a	2.12b
	RS	73.40b	9.60b	19.33a	2.14b

Note. Means followed by the same letter within a column are not significantly different according to the LSD test at $p < 0.05$

statistical group. These results indicate that the integrated treatment improved maize yield formation, particularly under the maize-soybean system.

A similar response was observed in upland rice, particularly under the upland rice-soybean (RS) system. P_1 increased panicle length from 23.40 to 25.78 cm, representing a 10.2% increase relative to P_0. Grain productivity increased from 4.01 to 5.20 t ha^{-1}, equivalent to a 29.7% increase. The increase in panicle length and productivity was statistically significant according to the LSD test, whereas the number of grains per panicle and 1000-grain weight did not differ significantly between P_0 and P_1. This suggests that the higher productivity under P_1 was associated more strongly with improved panicle development and overall yield formation than with changes in individual grain weight.

Soybeans also responded positively to the integrated nutrient treatment. In the MS system, productivity increased from 1.94 to 2.12 t ha^{-1} (9.3%), while in the RS system it increased from 1.70 to 2.14 t ha^{-1} (25.9%). Both increases were statistically significant based on the LSD test. The number of filled pods increased from 68.00 to 75.20 pods

plant^{-1} (10.6%) in MS and from 66.10 to 73.40 pods plant^{-1} (11.0%) in RS. In the RS system, P_1 also reduced the number of empty pods from 11.20 to 9.60 pods plant^{-1} (14.3%), although the 100-grain weight increased only numerically from 18.00 to 19.33 g and was not statistically different. These results suggest that the soybean productivity response was primarily associated with improved pod formation and reproductive performance rather than a significant increase in individual seed weight.

Overall, the productivity response demonstrates that the integrated biofertiliser-micronutrient treatment increased the yield of the component crops without increasing the recommended rate of inorganic fertilisers. The largest productivity increases were observed in maize under MS (19.9%), upland rice under RS (29.7%), and soybean under RS (25.9%) (Table 8). The response was therefore not uniform across crops or cropping systems, reflecting differences in crop nutrient requirements and yield formation. Nevertheless, because the cropping system × nutrient-management interaction was not statistically significant for the measured agronomic parameters, these differences should be interpreted as variation in the magnitude of response rather than evidence that P_1 was statistically more effective in a particular intercropping system.

The stronger responsiveness of soybeans to microbial and micronutrient inputs under intercropping may be linked to their symbiotic nitrogen-fixing capacity, which enhances nutrient acquisition and indirectly benefits companion cereals. Micronutrients such as Mo, Zn, and B supplied via fertilisation can stimulate nodulation, enzyme activation, and seed filling. According to Thapa et al. (2021), the role of Mo in soybeans is crucial for nodule formation and biological N_2 fixation by *Bradyrhizobium japonicum*. When Mo is deficient, nitrogen fixation is disrupted, and chlorosis symptoms appear on both young and old leaves. In maize and rice, improved cob and panicle development under P_1 is likely associated with enhanced availability of phosphorus and potassium from biofertiliser application, thereby supporting reproductive organ growth and grain filling.

The combination of biofertilisers (such as *Azotobacter*, AMF, and *Bacillus circulans*) and organic fertilisers (e.g., humic acid) has been shown to improve growth, yield, seed quality, and microbial and enzymatic activities, including phosphatase and dehydrogenase (Gao et al., 2020). Phosphate- and potassium-solubilising microbes enhance the uptake of N, P, and K in maize, thereby supporting grain filling and cob development (Ghetiya

Table 8
Increased Yield in an intercropping system with biofertiliser and micronutrient fertiliser treatments

Crop	Intercropping System	P0 (t ha^{-1})	P1 (t ha^{-1})	Increase
Maize	MS	5.72	6.86	19.9%
Upland rice	RS	4.01	5.20	29.7%
Soybean	MS	1.94	2.12	9.3%
Soybean	RS	1.70	2.14	25.9%

et al., 2018). Mehata et al. (2023) found that certain biofertilisers can improve important attributes such as panicle length and weight, 1,000-grain weight, and number of grains per panicle, as well as SPAD values, indicating a positive effect on grain filling and grain yield. Additionally, complementary rooting patterns and distinct nutrient demands among maize, rice, and soybean likely reduced interspecific competition, enabling more efficient resource use and contributing to the observed yield improvements.

Land-Use Efficiency and Cropping System Performance

The production of maize, dryland rice, and soybeans is calculated as the product of productivity and the number of plants cultivated in each intercropping system, divided by the number of plants per hectare. Among the intercropping systems, the maize-soybean and upland rice-soybean intercropping systems had the most significant increase in production with the addition of Biofertiliser and micronutrients.

All intercropping systems had LER values more than one, indicating better land use and time efficiency than monoculture (Erythrina, 2022). The highest LER (1.56) was obtained from the upland rice-soybean combination, followed by maize-soybean and maize-upland rice (Figure 3). The maximum CSE value of 1.5 was likewise seen in upland rice-soybean intercropping (Figure 4).

The use of biofertiliser and micronutrients increased LER by 14.17% and CSE by 13.08%, indicating improved land productivity and cropping system efficiency. Farmers in the study area generally practice corn monoculture in a single planting season. However, market saturation at harvest means maize prices are depressed from the average US$ 0.33 kg^{-1} to as low as US$ 0.14-0.17 kg^{-1}. In this sense, intercropping offers a means of revenue stabilisation through crop diversity. The inclusion of legumes and upland rice provides yield resilience and price stability.

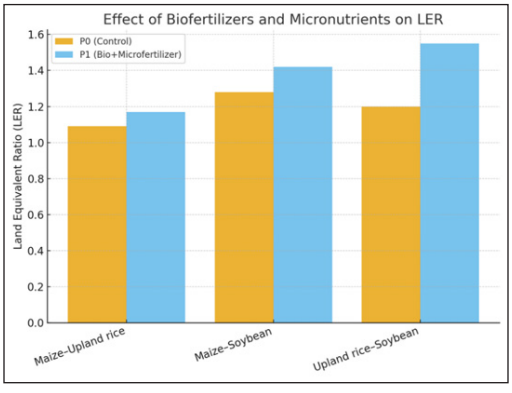

Figure 3. Effect of biofertilisers and micronutrients on Land Equivalent Ratio (LER)

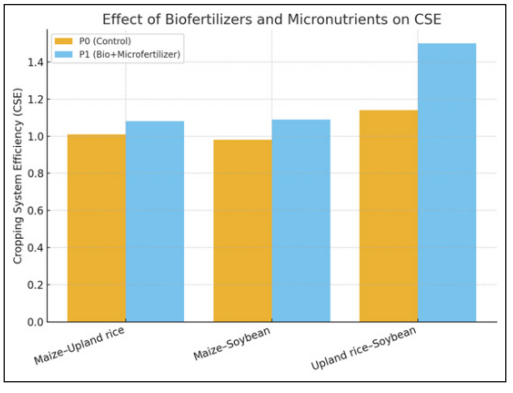

Figure 4. Effect of biofertilisers and micronutrients on Cropping System Efficiency (CSE)

The improved performance of the intercropping systems was attributed to increased productivity of the component crops. In instance, the RS system showed the strongest upland-rice productivity response and a significant soybean productivity improvement, matching its higher LER of 1.56 and CSE of 1.50. However, LER and CSE are system-level efficiencies and should be evaluated alongside the actual productivity of component crops, rather than as substitutes for crop yield measurements.

Economic Performance and Net Benefit

Financial analysis showed that all intercropping systems generated higher net benefits than the existing maize monoculture (US$742.40 ha^{-1}; R/C ratio = 1.68), although the magnitude varied among cropping systems (Table 9). Under P_1, net benefits reached US$840.70, US$1,230.40, and US$1,349.10 ha^{-1} in maize-upland rice, maize-soybean, and upland rice-soybean, respectively. Relative to maize monoculture, these values represented increases of 13.24%, 65.73%, and 81.72%, respectively (Table 10). Thus, the greatest economic advantage was achieved with the upland rice-soybean system under integrated biofertiliser-micronutrient management.

The addition of biofertiliser and micronutrients increased net benefit compared with P_0 in all intercropping systems, although the magnitude differed among systems. Net benefit increased from US$800.10 to US$840.70 ha^{-1} in maize-upland rice, from US$1,064.20 to US$1,230.40 ha^{-1} in maize-soybean, and from US$910.70 to US$1,349.10 ha^{-1} in upland rice-soybean. The corresponding R/C ratios were 1.63, 1.93, and 2.01 under P_1, respectively. The slightly lower R/C ratio in maize-upland rice under P_1 (1.63) than under P0 (1.65), despite the higher net benefit, indicates that the additional production costs were disproportionate to the increase in revenue. Therefore, net benefit and R/C ratio should be considered together when evaluating the economic performance of the integrated treatment.

The higher economic returns from intercropping resulted from the combined value of the component crops harvested from the same land area and the diversification of production. This diversification may reduce farmers' dependence on maize alone and provide greater flexibility under commodity price fluctuations. However, the superior economic performance of upland rice-soybean under P_1 should not be interpreted as evidence of a significant cropping system × nutrient-management interaction, because the interaction was not statistically significant for the measured agronomic variables. Rather, its higher economic return reflects the combined effects of crop productivity, crop composition, production costs, and prevailing crop prices during the experimental period.

Overall, all intercropping systems studied were economically feasible, with R/C ratios ranging from 1.63 to 2.01 under P_1. The upland rice-soybean system had the best net benefit and R/C ratio, indicating strong economic potential under current production and market conditions. Nevertheless, these results reflect the pricing and cost conditions

Table 9
Financial performance of intercropping systems under standard and enhanced fertilisation strategies

Intercropping Systems	Revenue (R) (US$)		Production Cost (C) (US$)		Benefit (B) (US$)		R/C	
	P_0	P_1	P_0	P_1	P_0	P_1	P_0	P_1
MR	2.026.4	2.175.4	1.226.3	1.334.7	800.1	840.7	1.65	1.63
MS	2.249.5	2.549.4	1.185.3	1.319.0	1.064.2	1.230.4	1.90	1.93
RS	2.127.6	2.684.5	1.216.9	1.335.4	910.7	1.349.1	1.75	2.01
Maize Monoculture (existing)	1.834.4		1.092.0		742.4		1.68	

Table 10
Increased benefit in an intercropping system with biofertiliser and micronutrient fertiliser treatments

Intercropping Systems	Benefit P_0	Benefit P_1	Increase vs. Monoculture P_0	Increase vs. Monoculture P_1	Mean
MR	800.10	840.70	7.77%	13.24%	10.51%
MS	1.064.20	1.230.40	43.35%	65.73%	54.54%
RS	910.70	1.349.10	22.67%	81.72%	52.20%
Maize Monoculture	742.40				

during the experiment and should not be taken as evidence that income will be stable over the long run. Additional sensitivity analysis incorporating changes in crop prices and production costs would be useful to determine the robustness of the economic advantage under unfavorable market conditions.

The results indicate that intercropping-based diversification is a risk-mitigation strategy against market volatility. Furthermore, the positive R/C ratios (>1) in all the treatments illustrate the economic viability and sustainability of the proposed systems for the farmers. This is consistent with previous studies showing that intercropping promotes income stability by spreading risk across different commodities (Hermawati, 2016).

The results encourage the adoption of intercropping systems in association with environmentally friendly fertilisation practices. Biofertilisers are microbiologically active, low-impact, environmentally safe, and improve soil structure, water infiltration, and aggregate stability (Martirosyan et al., 2023; Stehlík et al., 2019). Small amounts of inorganic fertilisers (Urea, NPK, and micronutrients) are used in regulated doses to augment organic inputs without causing soil degradation or contamination.

Therefore, the simultaneous use of biofertiliser, micronutrients, and site-specific inorganic fertilisers is a feasible approach to intensify drylands sustainably. These innovations are agronomically and commercially practicable, with R/C ratios>1 across all treatments (Ely & Darwanto, 2014; Msiska et al., 2024), and may serve as a paradigm for large-scale adoption in areas with similar agroecological limitations.

Mechanisms Underlying the Response to Integrated Biofertiliser and Micronutrient Management

The higher crop growth and production under the integrated biofertiliser-micronutrient treatment (P1) may be due to the combined effects of biological nutrient cycling and micronutrient application. The reaction was more pronounced at 6-8 weeks after planting (WAP), when the nutritional demand of the crops was higher, as evidenced by increased plant height in maize, upland rice, and soybean, and accelerated tiller development in upland rice and branch formation in soybean. This pattern is consistent with improved fertiliser supply through integrated treatment during the period of increasing crop demand. Nevertheless, as food consumption, microbial activity and nutrient fluxes were not clearly defined, these mechanisms should be treated as reasonable interpretations and not directly demonstrated processes.

Biofertilisers can improve the intake of plant nutrients by several microbial activities, including biological nitrogen transformation, phosphorus solubilisation, potassium mobilisation and generation of plant growth-stimulating chemicals. These microorganisms can change the availability of nutrients in the rhizosphere and support the roots of the plant in absorbing and using up nutrients (Mahanty et al., 2017; Soumare et al., 2020). For instance, phosphate-solubilising bacteria can render rarely accessible P mobile by

organic acid synthesis, proton release and enzymatic mineralisation. However, responses to microbial inoculants in the field can vary, as their efficiency depends on soil properties, native microbial populations, environmental conditions, and the establishment of the imported microorganisms (Raymond et al., 2021). Hence, the higher response at later growth stages could perhaps be explained by rising crop demand together with microbial-mediated nutrient cycling rather than an increase in the availability of nutrients in soil, as indicated in our experiment.

Micronutrient addition may have contributed to these biological processes, supporting important physiological and enzymatic functions. Small quantities of elements such as zinc, iron, manganese, boron and molybdenum are needed for enzyme activation, photosynthesis, reproductive development and food metabolism. Micronutrients play important roles in soybeans, and their deficiencies can impede growth, nodulation, and reproductive development (Bagale, 2021; Thapa et al., 2021). Therefore, the micronutrient component of P_1 may have improved the efficiency of physiological processes responsible for biomass synthesis and yield production, complementing the macronutrients supplied by the proposed fertilisation technique.

The soybean response is of particular interest since the symbiotic biological nitrogen fixation (BNF) may be a source of N nutrition. P and micronutrients, in particular, are important for nodule formation and nitrogenase activity, and their optimal availability is critical for effective BNF. Molybdenum is directly linked to nitrogenase activity, and other micronutrients also play roles in enzymatic and physiological processes that support the symbiotic relationship. Therefore, the increased branching, filled-pod development, and seed yield observed at P1 are consistent with more favourable nutritional conditions, which may improve soybean growth and symbiotic N acquisition. However, the present observations cannot be taken as a direct indication of increased biological nitrogen fixation by P1 because no data were obtained on nodulation, nitrogenase activity, or N_2 fixation.

The intercropping environment may have also contributed to the response through complementary utilisation of soil resources. Maize, upland rice and soybean have different rooting characteristics, nutritional requirements and crop development; therefore, they may compete less directly for light, water and nutrients. Therefore, the additional nutrients released by the integrated management may have been utilised by the component crops according to their distinct temporal and spatial demands. This interpretation is consistent with the higher land-use efficiency observed in intercropping systems, particularly in upland rice-soybean. However, the absence of a significant cropping system × nutrient-management interaction suggests that the positive response to P_1 was not statistically specific to a particular crop combination.

Overall, the results indicate that the benefit of combining biofertiliser and micronutrients with the recommended mineral fertilisation is likely due to complementary nutrient-

management functions: the biofertiliser may have improved biological nutrient cycling and mobilisation, while the micronutrients are involved in essential physiological and reproductive processes. These complementary effects could plausibly explain the higher growth, yield components and productivity under P_1 without raising the recommended rate of mineral fertilisers. Nonetheless, to verify these proposed mechanisms and to assess if treatment results in longer-term improvements in soil biological and chemical properties, direct measurements of microbial biomass and activity, soil nutrient availability, root traits, plant nutrient uptake, nodulation, and biological N fixation are needed.

CONCLUSION

Application of biofertilisers and micronutrients combined with the locally recommended inorganic fertilisation increased the crop growth, yield and overall productivity of the studied cereal-legume intercropping systems. In all intercropping systems, the Land Equivalent Ratio (LER) was greater than one, indicating that land was used more efficiently than in monocropping. Among the investigated systems, Upland rice-soybean had the highest LER (1.56) and Cropping System Efficiency (CSE) (1.50). The integrated nutrient treatment also yielded positive economic returns, with R/C ratios above unity across all intercropping systems. The upland rice-soybean system provided the highest economic return with an R/C ratio of 2.01.

The absence of a significant cropping system × nutrient-management interaction indicates that the positive agronomic response to biofertiliser and micronutrient supplementation was not statistically dependent on a particular intercropping combination. Therefore, the integrated nutrient-management approach can be considered a broadly applicable option for improving the productivity and economic performance of cereal-legume intercropping systems under the tested dryland conditions.

IMPLICATIONS OF THE STUDY

The findings support the use of biofertiliser and micronutrients as complementary inputs to locally recommended inorganic fertilisation for sustainable intensification of dryland agriculture.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

However, the present study did not directly measure changes in soil microbial biomass, microbial activity, soil organic carbon, enzyme activity, aggregate stability, nutrient availability, or plant nutrient uptake after treatment. Therefore, improvements in soil health or soil fertility should not be considered a direct outcome of this experiment. The potential contribution of the integrated treatment to soil biological and chemical quality requires further verification.

For wider application, the recommended nutrient-management package should first be validated through multi-season and multi-location trials under dryland environments with similar agroecological conditions. Future studies should additionally quantify soil biological properties, soil organic carbon, nutrient availability, root characteristics, plant nutrient uptake, and biological nitrogen fixation to elucidate the mechanisms underlying the observed agronomic and economic responses and to determine the longer-term effects of integrated nutrient management on soil health.

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