

ORIGINAL RESEARCH ARTICLE

Diversifying cropping systems to enhance productivity using agroforestry trees: A case study of maize–pigeon pea intercropping in Ghana

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Abstract

Amid growing global challenges such as population growth, climate change, and limited natural resources, the need for sustainable farming systems to ensure food security and environmental conservation has become increasingly critical. This study – conducted in the forest zones of Ghana during the major and minor cropping seasons of 2023 – evaluates the effects of integrating *Cajanus cajan* (also known as pigeon pea), a leguminous shrub, into a maize cropping system. This maize–pigeon pea (MPP) intercropping approach is part of an innovative integrated soil fertility management strategy aimed at improving maize yield, farm profitability, and climate resilience of smallholder farmers. A split-plot experimental design was employed, with the cropping systems – MPP intercrop and sole maize – as main plots, and varying recommended inorganic fertilizer (full rate [FR], half rate [HR], and a no-fertilizer control) as subplots. The findings revealed a significant association between the MPP intercropping system and the rate of inorganic fertilizer application on maize growth and yield, with improved and comparable maize productivity observed when either the HR or FR fertilizer was applied. This suggests that integrating pigeon peas and their biomass could reduce the recommended fertilizer rate by half, thereby enhancing farmers' income and profitability while promoting sustainable maize production amid climate change. Future research should explore long-term soil fertility dynamics and broader agroecological applications.

Keywords: Agroforestry; Climate change; Integrated soil fertility management; Maize; Pigeon pea; Resource utilization

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1. Background and rationale

The escalating global demand for food production requires urgent attention to the challenges associated with agricultural intensification, particularly in resource-limited

regions such as Ghana and other parts of Africa, where smallholder farming systems predominate.^{1,2} Sustainable agriculture is a crucial strategy for reducing environmental damage and ensuring the long-term sustainability of these farming systems.³ Understanding the factors that influence farmers' adoption of sustainable practices is essential to promote their widespread implementation.³ In Ghana, maize (*Zea mays*) – a major staple crop – continues to face significant productivity challenges due to declining soil fertility and unpredictable climate changes.^{4,5} These challenges are further intensified by continuous monocropping and inadequate application of soil amendments.⁶ Despite the increase in maize production over the past decade, this growth is largely driven by the expansion of cultivated areas rather than improvements in yield per unit area.⁷ This trend highlights the urgent need for integrated soil fertility management (ISFM) strategies to enhance and maintain maize productivity.^{8–11}

One promising approach to improving maize productivity and sustainability is the integration of pigeon pea (*Cajanus cajan*), a nutrient-rich legume, into maize-based cropping systems. Pigeon pea has the capacity to fix atmospheric nitrogen through biological nitrogen fixation, thereby enhancing soil fertility and reducing the need for synthetic nitrogen fertilizers. This can lower production costs for farmers while mitigating the environmental risks associated with excessive fertilizer use. Previous studies have demonstrated that intercropping pigeon pea can improve soil structure and nutrient availability, benefiting maize and other associated crops.^{12–14} The combined use of organic and inorganic fertilizers has the potential to improve soil health, mitigate climate-related risks, and offer a cost-effective strategy for smallholder farmers. In addition, pigeon pea's protein-rich grains can enhance household nutrition and food security.

Pigeon pea is increasingly recognized as a valuable agroforestry crop – particularly in tropical and subtropical regions – due to its resilience and ability to improve soil fertility.^{12,15,16} When intercropped with maize, pigeon pea offers numerous agronomic benefits, including biological nitrogen fixation, enhanced soil structure, and reduced reliance on synthetic fertilizers.⁸ Furthermore, pigeon pea contributes to ecosystem sustainability by supporting soil erosion control, biodiversity conservation, and increased reliance to climate variability.^{8,15}

Despite these benefits, the success of maize–pigeon pea (MPP) intercropping largely depends on various factors, including agronomic practices, environmental conditions, and socioeconomic factors.^{8,13} Unlike previous studies, this research employs a comprehensive approach

to assess MPP intercropping. It examines agronomic performance, economic viability, and long-term soil fertility effects – areas that remain unexplored in Ghana. Furthermore, the research is grounded in ethnobotanical principles, highlighting the traditional knowledge and cultural importance of pigeon pea cultivation among local farmers. The integration of traditional cropping systems and local adaptation strategies distinguishes this study from conventional agronomic studies.^{5,17}

The primary objective of this study is to evaluate the agronomic and economic benefits of MPP intercropping, focusing on increased crop yields, reduced reliance on inorganic fertilizers, and improved soil health. By assessing the performance of this system in Ghana's forest zones, the research aims to provide valuable insights into its impact on maize productivity, soil fertility, and the climate resilience of smallholder farmers. Ultimately, the study aims to optimize resource use and advance sustainable maize production amid ongoing environmental challenges. The findings are anticipated to advance the current understanding of agroforestry, ISFM, and sustainable cropping systems, thereby supporting policy development, improving agricultural practices, and guiding future research efforts.

2. Materials and methods

2.1. Study location

This study was conducted between 2022 and 2024 at the Council of Scientific and Industrial Research (CSIR)–Crops Research Institute in Fumesua, Ghana (latitude: 6.7155729; longitude: –1.5316034; [Figure 1](#)). The site is located in the humid forest agroecological zone, characterized by Ferric Acrisol soils with a sandy clay loam topsoil. This region experiences a bimodal rainfall distribution, with the major rainy season occurring from March to mid-August and the minor season from September to November. Annual rainfall averages between 1,027 mm and 1,322 mm ([Table 1](#) and [Figure 2](#)).

2.2. Experimental design and intercropping arrangement

A split-plot design with four replications was employed. The main plot treatments comprised two cropping systems ([Figure 3](#)):

- (i) MPP intercropping.
- (ii) Maize monoculture (no pigeon pea [NPP]).

The subplots included three fertilizer treatments:

- (i) Full rate (FR): 250 kg/ha of 15-15-15 nitrogen-phosphorus pentoxide-potassium oxide (N-P₂O₅-K₂O) + 250 kg/ha of sulfate of ammonia (SoA).

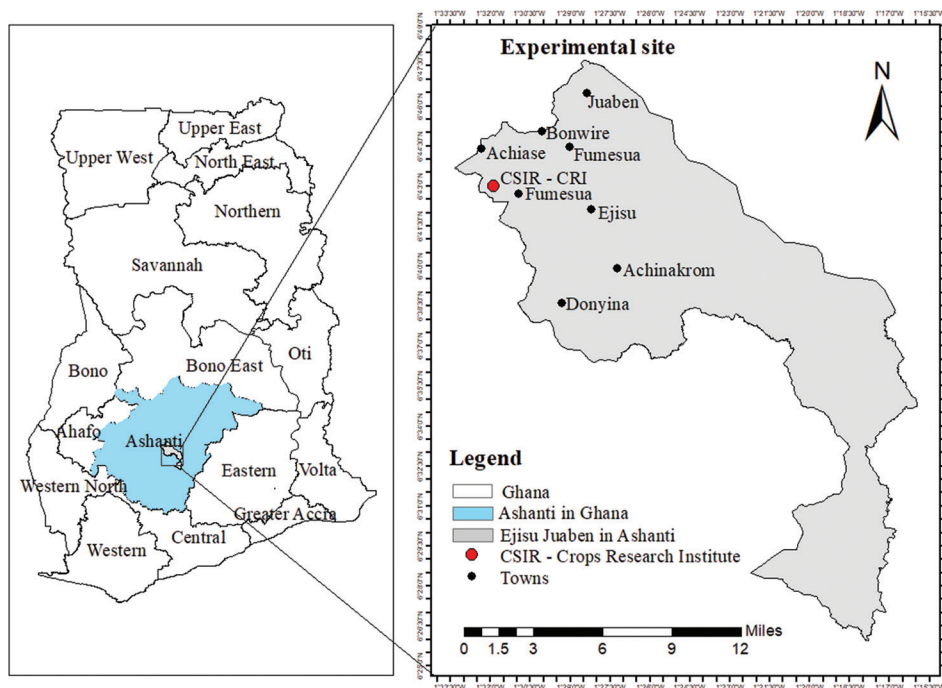


Figure 1. Location map of Ghana showing the CSIR–Crops Research Institute site in Fumesua (indicated by a red circle), where the research was conducted between 2022 and 2024

Abbreviation: CSIR: Council of Scientific and Industrial Research.

Table 1. Study location characteristics

Characteristics	Fumesua (6° 41' N, 1° 28' W)
Agroecological zone	Humid forest
Soil type	Ferric Acrisol, specifically the Asuasi series. The upper topsoil consisted of approximately 5 cm of grayish–brown sandy loam and dark brown, gritty clay loam
Temperature (min–max, °C) from 2020 to 2023	21 – 37°C
Rainfall pattern	Bimodal rainfall distribution
Major raining season	March–mid-August
Minor raining season	September–November, peak in October
Total annual rainfall (mm), from 2020 to 2023	1,027 – 1,322 mm, averaging at 1,184 mm/year

Source: Adopted from Adu and Asiamah.¹⁸

- (ii) Half rate (HR): 125 kg/ha of 15-15-15 N-P₂O₅-K₂O + 125 kg/ha of SoA.
- (iii) No fertilizer (NF): Control treatment without inorganic fertilizer application.

Pigeon pea was planted during the minor season of 2022 to allow sufficient biomass accumulation for incorporation into the soil during the 2023 cropping seasons. A late-maturing pigeon pea variety (8 months to maturity) was selected and used to maximize biomass production. The maize variety used was *Abontem*, an improved open-pollinated variety developed by the CSIR–Crops Research Institute.

Planting and crop management:

- (i) NPP: Maize was planted at a spacing of 0.8 m × 0.4 m with two plants per hill, following CSIR–Crops Research Institute guidelines,⁴ resulting in a population density of 62,500 plants/ha. Two central maize plots were designated for data collection, with adjacent rows used for destructive sampling.
- (ii) MPP: A substitution model allocated approximately 30% of the maize area to pigeon pea by alternating six rows of maize with two rows of pigeon peas. Pigeon peas were planted at a spacing of 1 m × 5.6 m (intra-row and inter-row spacing respectively), resulting in a population density of 3,571 plants/ha, while maize

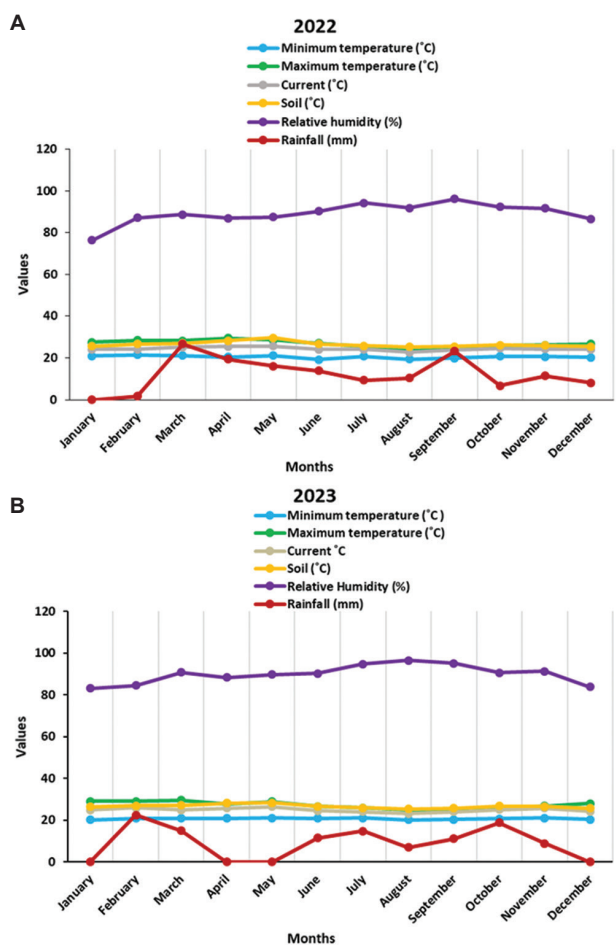


Figure 2. Monthly weather parameters recorded in Fumesua in 2022 (A) and 2023 (B), including rainfall distribution, temperature trends, and relative humidity levels

density was 4,875 plants/ha. Similar to NPP, the two central maize rows were used for data collection and adjacent rows for destructive sampling.

(iii) Pigeon pea monoculture: Adjacent sole pigeon pea plots were established to calculate land equivalent ratios [LERs]. Pigeon pea was planted at 1 m × 0.5 m spacing, resulting in a population of 40,000 plants/ha. Planted in 2022, pigeon pea was managed as a perennial crop, while maize was grown during the major and minor seasons of 2023. Fresh pigeon pea biomass of 2,210 and 1,620 kg/ha was evenly incorporated into the soil in intercrop plots during the major and minor seasons of 2023, respectively.

(iv) Fertilizer application: 15-15-15 N-P₂O₅-K₂O fertilizer was applied 2 weeks after planting, followed by SoA at 6 – 8 weeks.⁴

2.2.1. Measurements and determination of LER

Maize was harvested at physiological maturity, and all cobs from the designated harvest area were weighed to

determine plot yield (kg). A total of 20 cobs from each plot were shelled to measure fresh grain weight, and shelling recovery was calculated as the ratio of fresh grain weight to the total weight of the 20 cobs. Similarly, pigeon pea grain yield was determined at physiological maturity by shelling all pods from the harvest and recording the fresh grain weight (kg). Grain moisture content for both maize and pigeon peas was measured using a universal grain moisture meter (INDOSAN S6010, Indosaw, India), and grain yields were adjusted to a standardized moisture content of 15%, with final yields expressed in tons/ha, as indicated in the equations.

$$\text{Adjusted moisture content (MC}_{\text{adj}}) = \frac{100 - \text{Actual moisture content}}{100 - \text{Desired moisture content}} \quad (\text{I})$$

$$\text{Grain yield (tons/ha at 15\% MC}_{\text{adj}}) = \frac{\text{Plot yield (kg)} \times 10,000 \text{ m}^{-2} \times \text{MC}_{\text{adj}} \times \text{SR\%}}{12 \text{ m}^{-2} \times 1,000} \quad (\text{II})$$

To compare the productivity of monoculture and MPP intercropping, the LER was employed, calculated as follows:

$$\text{LER} = \frac{Y_m I}{Y_m S} + \frac{Y_p I}{Y_p S} \quad (\text{III})$$

Where:

- Y_mI is maize yield under intercropping (tons/ha),
- Y_mS is maize yield under sole cropping (tons/ha),
- Y_pI is pigeon pea yield under intercropping (tons/ha),
- Y_pS is pigeon pea yield under sole cropping (tons/ha).

An LER value greater than 1 indicates a yield advantage of intercropping over sole cropping, while a value <1 indicates a disadvantage.^{19,20}

2.3. Data collection and statistical analysis

Data on the growth, biomass, and grain yields of maize and pigeon peas were analyzed using a three-way analysis of variance (cropping system × fertilizer × experimental season) with type III error at a 5% significance level (*p*<0.05). Analyses were performed using Jeffreys’s Amazing Statistics Program (version 0.19.1.0, University of Amsterdam, Netherlands), available at <https://jasp-stats.org>.²¹ Before analysis, the homogeneity of variances was verified using the Shapiro–Wilk and Levene’s tests. When significant differences were observed among treatment means, Tukey’s Honestly Significant Difference test was employed for mean separation, with groupings indicated using letter annotations.

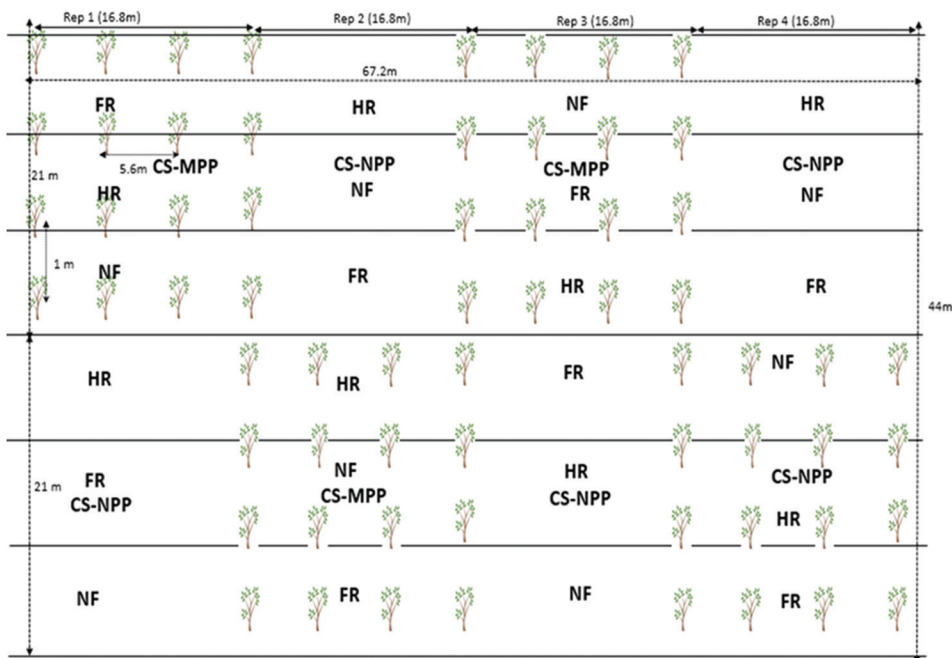


Figure 3. Plot design for maize–pigeon pea intercropping and sole maize plots at the CSIR–Crops Research Institute site in Fumesua, Ghana
Abbreviations: CS: Cropping system; FR: Full rate; HR: Half rate; MPP: Maize–pigeon pea intercropping; NF: No fertilizer; NPP: No pigeon pea/sole maize; Rep: Replicate; CSIR: Council of Scientific and Industrial Research.

3. Results

Analysis of variance across the two experimental seasons (major and minor cropping seasons) in 2023 at the CSIR–Crops Research Institute site in Fumesua shows significant factor interactions ($p < 0.05$). Consequently, growth and yield results across seasons, cropping systems, and fertilizer treatments are presented in Tables 2 & 3, and Figure 4.

3.1. Growth of maize in the MPP cropping system and fertilizer treatment

The growth performance of maize in the MPP cropping system provides valuable insights into the interaction of cropping systems, fertilizer application, and seasonal variation on growth parameters. This analysis focused on plant height, estimated leaf area, fresh leaf biomass, and dry leaf biomass, providing a comprehensive understanding of the trade-offs and synergies between intercropping and monoculture systems.

3.1.1. Plant height

Maize height growth was consistently higher with FR fertilizer across both cropping systems and seasons, peaking in the NPP system during the minor season (201.7 cm, Table 2). This highlights the critical role of nutrient availability in promoting vertical growth. The superior height observed in fertilized treatments during the minor

season suggests favorable environmental conditions, such as optimal rainfall, which enhance fertilizer efficiency. In contrast, maize without fertilizer (NF) recorded the lowest heights, particularly in the intercrop system during the major season (Table 2). This suggests that competition for resources in intercropping systems may further limit growth under nutrient-poor conditions.

3.1.2. Estimated leaf area

Leaf area – an indicator of photosynthetic capacity – followed a similar trend, with FR treatments significantly outperforming others (Table 2). The NPP system with FR treatment in the minor season recorded the largest leaf area (9,751.3 cm²), indicating reduced competition for light and nutrients (Table 2). While leaf area was lower under NF treatment, the MPP intercrop system demonstrated stability with the HR treatment, particularly in the minor season. This suggests that intercropping with pigeon peas may buffer maize against environmental stress by providing benefits such as nitrogen fixation and improved soil nutrition. However, the reduced leaf area in intercrops under low fertilizer conditions indicates a trade-off, where intercropping benefits are insufficient to fully offset resource competition (Table 2).

3.1.3. Fresh and dry leaf biomass

Biomass production – an integrative measure of growth performance – was the highest in the NPP with FR

Table 2. Maize growth parameters – height (cm), leaf area (cm²), fresh leaf biomass (g), and dry leaf biomass (g) – in pigeon pea-maize intercrop and sole maize systems during the major and minor 2023 seasons in Fumesua, Ghana

Trait	Cropping system	Fertilizer	Season	Mean	SD	SE	Rank	CV		
Plant height (cm)	MPP	FR	Major	183.333	27.429	15.836	a, b, and c	0.150		
		FR	Minor	188.600	10.800	6.235	a, b, and c	0.057		
		HR	Major	171.667	4.041	2.333	a, b, and c	0.024		
		HR	Minor	183.733	12.232	7.062	a, b, and c	0.067		
		NF	Major	165.667	6.028	3.480	a and b	0.036		
		NF	Minor	183.200	11.459	6.616	a, b, and c	0.063		
		NPP	FR	Major	186.333	12.897	7.446	a, b, and c	0.069	
	NPP	FR	Minor	201.733	5.991	3.459	c	0.030		
		HR	Major	183.000	1.732	1.000	a, b, and c	0.009		
		HR	Minor	199.800	6.264	3.617	b and c	0.031		
		NF	Major	155.000	8.660	5.000	a	0.056		
		NF	Minor	190.667	10.576	6.106	b and c	0.055		
		Estimated leaf area (cm ²)	MPP	FR	Major	3,344.000	1,111.367	641.648	a and b	0.332
				FR	Minor	5,971.227	1,262.122	728.687	b and c	0.211
HR	Major			2,444.833	722.885	417.358	a	0.296		
HR	Minor			6,222.638	854.590	493.398	b and c	0.137		
NF	Major			2,531.600	656.660	379.123	a	0.259		
NF	Minor			5,248.935	1,299.948	750.525	a, b, and c	0.248		
NPP	FR			Major	3,324.267	1,606.432	927.474	a and b	0.483	
NPP	FR		Minor	9,751.329	2,250.264	1,299.190	d	0.231		
	HR		Major	2,832.987	1,044.594	603.096	a and b	0.369		
	HR		Minor	7,609.492	451.322	260.571	c and d	0.059		
	NF		Major	2,377.856	488.550	282.064	a	0.205		
	NF		Minor	5,462.927	840.269	485.129	a, b, and c	0.154		
	Fresh leaf biomass (g)		MPP	FR	Major	15,614.993	1,767.147	1,020.263	a	0.113
				FR	Minor	25,158.700	6,642.259	3,834.910	b	0.264
HR		Major		13,638.263	2,818.075	1,627.017	a	0.207		
HR		Minor		19,418.467	1,210.187	698.702	a and b	0.062		
NF		Major		13,558.767	1,453.365	839.101	a	0.107		
NF		Minor		11,699.450	3,185.983	1,839.428	a	0.272		
NPP		FR		Major	16,528.237	2,614.294	1,509.363	a	0.158	
NPP		FR	Minor	25,605.358	11,597.683	6,695.926	b	0.453		
		HR	Major	14,281.808	2,982.279	1,721.820	a	0.209		
		HR	Minor	22,687.292	10,530.918	6,080.028	b	0.464		
		NF	Major	14,851.900	4,626.948	2,671.370	a	0.312		
		NF	Minor	11,164.533	2,197.746	1,268.869	a	0.197		
		Dry leaf biomass (g)	MPP	FR	Major	6,692.140	757.349	437.256	a	0.113
				FR	Minor	10,782.300	2,846.682	1,643.533	b	0.264
HR	Major			5,844.970	1,207.747	697.293	a	0.207		
HR	Minor			8,322.200	518.652	299.444	a and b	0.062		
NF	Major			5,810.900	622.871	359.615	a	0.107		
NF	Minor			5,014.050	1,365.421	788.326	a	0.272		
NPP	FR			Major	7,083.530	1,120.412	646.870	a	0.158	
NPP	FR		Minor	10,973.725	4,970.436	2,869.682	b	0.453		
	HR		Major	6,120.775	1,278.120	737.923	a	0.209		
	HR		Minor	9,723.125	4,513.250	2,605.726	a and b	0.464		
	NF		Major	6,365.100	1,982.978	1,144.873	a	0.312		
	NF		Minor	4,784.800	941.891	543.801	a	0.197		

Note: Means with the same alphabet ranking are not significantly different from each other. Abbreviations: CV: Coefficient of variation; FR: Full rate of recommended fertilizer; HR: Half rate of recommended fertilizer; MPP: Maize–pigeon pea; NF: No fertilizer; NPP: No pigeon pea/sole maize; SD: Standard deviation; SE: Standard error.

Table 3. Maize yield components (cob number, cob weight per plant, hundred-seed weight, and total grain yield) in pigeon pea-maize intercrop and sole maize systems during the major and minor 2023 seasons in Fumesua, Ghana

Trait	Cropping system	Fertilizer	Season	Mean	SD	SE	Rank	CV		
Cob number	MPP	FR	Major	53.667	3.055	1.764	a	0.057		
		FR	Minor	125.667	12.097	6.984	b	0.096		
		HR	Major	45.667	7.767	4.485	a	0.170		
		HR	Minor	122.667	2.082	1.202	b	0.017		
		NF	Major	54.667	9.074	5.239	a	0.166		
		NF	Minor	56.000	24.759	14.295	a	0.442		
	NPP	FR	Major	59.000	1.732	1.000	a	0.029		
		FR	Minor	205.667	125.437	72.421	b and c	0.610		
		HR	Major	48.667	10.693	6.173	a	0.220		
		HR	Minor	104.667	21.572	12.454	b	0.206		
		NF	Major	57.333	8.083	4.667	a	0.141		
		NF	Minor	31.667	16.073	9.280	a	0.508		
		Total cob weight (g)	MPP	FR	Major	836.333	135.664	78.326	a	0.162
				FR	Minor	14,698.767	3,935.081	2,271.920	d and e	0.268
HR	Major			858.600	144.849	83.628	a	0.169		
HR	Minor			11,344.533	725.511	418.874	b, c, and d	0.064		
NF	Major			714.733	65.655	37.906	a	0.092		
NF	Minor			4,327.733	2,129.132	1,229.255	a, b, and c	0.492		
NPP	FR		Major	803.133	146.879	84.801	a	0.183		
	FR		Minor	22,279.567	8,443.772	4,875.014	e	0.379		
	HR		Major	844.933	110.630	63.873	a	0.131		
	HR		Minor	12,909.800	5,939.399	3,429.113	c, d, and e	0.460		
	NF		Major	733.633	153.568	88.662	a	0.209		
	NF		Minor	2,488.833	1,686.059	973.447	a and b	0.677		
	Hundred-seed weight (g)		MPP	FR	Major	33.500	6.384	3.686	b	0.191
				FR	Minor	27.167	0.666	0.384	b	0.025
HR		Major		32.833	7.943	4.586	b	0.242		
HR		Minor		32.467	6.401	3.696	a and b	0.197		
NF		Major		28.833	1.041	0.601	b	0.036		
NF		Minor		21.733	8.601	4.966	a	0.396		
NPP		FR	Major	37.333	5.008	2.892	b and c	0.134		
		FR	Minor	31.333	3.828	2.210	a and b	0.122		
		HR	Major	37.000	4.770	2.754	b and c	0.129		
		HR	Minor	34.033	6.809	3.931	b	0.200		
		NF	Major	33.167	2.930	1.691	b	0.088		
		NF	Minor	28.533	1.007	0.581	b	0.035		
		Total grain yield (tons/ha)	MPP	FR	Major	6.468	1.808	1.044	b	0.280
				FR	Minor	3.892	0.694	0.401	a and b	0.178
HR	Major			6.096	0.628	0.362	b	0.103		
HR	Minor			3.755	0.673	0.388	a and b	0.179		
NF	Major			3.848	0.470	0.271	a and b	0.122		
NF	Minor			2.481	0.394	0.227	a	0.159		
NPP	FR		Major	5.819	1.590	0.918	b	0.273		
	FR		Minor	3.836	1.057	0.610	a and b	0.275		
	HR		Major	6.037	1.234	0.712	b	0.204		
	HR		Minor	3.745	0.880	0.508	a and b	0.235		
	NF		Major	4.349	0.936	0.540	a and b	0.215		
	NF		Minor	1.999	0.809	0.467	a	0.405		

Abbreviations: CV: Coefficient of variation; FR: Full rate of recommended fertilizer; HR: Half rate of recommended fertilizer; MPP: Maize–pigeon pea; NF: No fertilizer; NPP: No pigeon pea/sole maize; SD: Standard deviation; SE: Standard error.

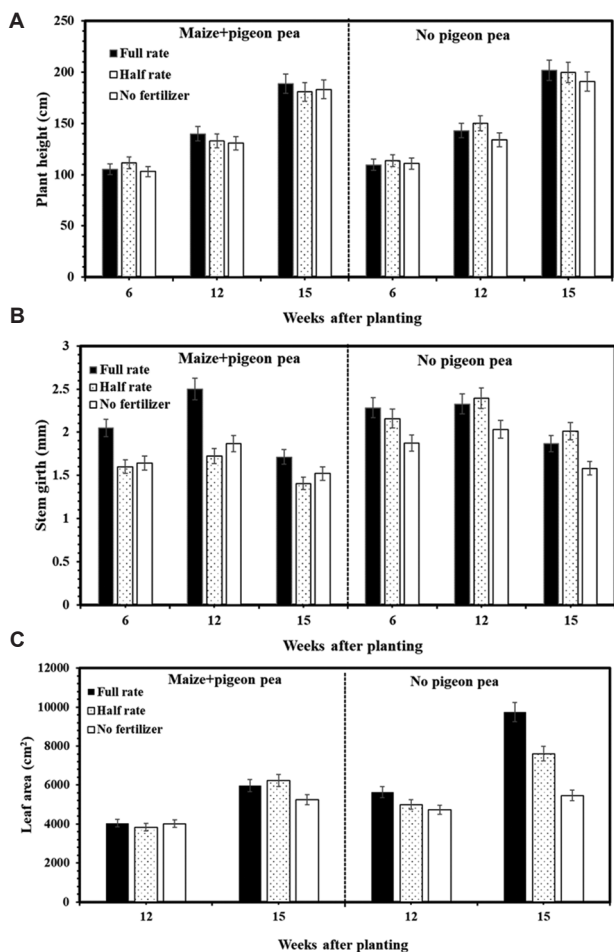


Figure 4. Growth measurements of maize height (A), stem girth (B), and leaf area (C) in maize–pigeon pea intercropping and sole maize plots, recorded at 6–15 weeks after planting during the minor season of 2023

treatment during the minor season (fresh = 25,605.4 g; dry = 10,973.7 g; Table 2). This highlights the system’s ability to effectively utilize high nutrient inputs when resource limitations – such as light and space – are minimal. Conversely, the MPP intercrop system exhibited lower biomass under NF but maintained competitive performance under HR, particularly in the minor season (Table 2). This suggests that intercropping can sustain reasonable productivity with moderate inputs, supporting principles of sustainable agriculture (Table 2).

3.1.4. Seasonal variation and system dynamics

Seasonal effects were pronounced, with growth improving in the minor season across all treatments, likely due to the accumulation of soil organic matter and nitrogen fixation from pigeon pea biomass incorporation (Table 2). In the intercrop system, HR treatments balanced growth and resource use, showing adaptive potential under moderate nutrient levels (Table 2). The NPP system performed well

under FR but showed greater variability under low-input conditions, indicating lower resilience than intercropping (Table 2).

These findings highlight a key trade-off: NPP systems excel under high input conditions but are vulnerable to nutrient and environmental constraints. In contrast, the MPP system prioritized stability and sustainability over peak productivity (Table 2). The intercrop system’s consistent growth under HR and its resilience to seasonal changes demonstrate its suitability for resource-limited environments. In addition, the ecological benefits of pigeon peas – such as nitrogen fixation, organic matter addition, and soil protection – provide long-term advantages beyond immediate growth measurements.

3.2. Maize growth as influenced by cropping system and fertilization

In the minor season experiment, the morphological growth patterns of maize in the MPP intercrop and NPP sole cropping systems were monitored from 6 to 15 weeks after planting. Plant height (cm), stem girth (mm), and leaf area (cm²) were recorded at each time point. Maize height showed no statistically significant differences between cropping systems and fertilizer treatments throughout the growth period (Figure 4A). However, the tallest plants were recorded at 15 weeks in the NPP system under FR treatment (Figure 4A). In contrast, stem girth exhibited significant differences between cropping systems and fertilizer treatments (Figure 4B), with the thickest stems observed in the NPP system under FR. The MPP system under NF treatment showed reduced stem girth development (Figure 4B).

From 12 to 15 weeks, maize leaf area (cm²) showed significant differences among fertilizer treatments and cropping systems (Figure 4C). The highest mean leaf area was recorded in the NPP system under FR, followed by HR and NF, all of which are significantly higher than the intercrop plants (Figure 4C).

3.3. Yield component of maize

Maize yield components were analyzed across the MPP intercrop and NPP systems under different fertilizer levels and seasons (Table 3). Key traits – including number of cobs per plant, cob weight, hundred-seed weight, and total grain yield – were evaluated to determine the effects of cropping system, fertilizer application, and seasonal variation on crop productivity (Table 3).

3.3.1. Cob number and weight

Cob numbers differed significantly across cropping systems and seasons. The MPP system recorded the highest cob

number under FR fertilizer treatment in the minor season (126 cobs), while NF treatment yielded the lowest counts (Table 3). In comparison, the NPP system produced the highest cob number (206 cobs) under FR treatment during the minor season, indicating that reduced competition in sole cropping enhances reproductive development under optimal nutrient conditions. Cob weight followed this pattern, with the NPP system under FR treatment in the minor season achieving the highest cob weight (22,279.6 g), underscoring the NPP system’s ability to maximize biomass production under high nutrient input (Table 3).

3.3.2. Hundred-seed weight

Hundred-seed weight was generally higher in the NPP system under FR treatment, with the highest value recorded during the major season (37.3 g, Table 3). FR treatment also resulted in competitive seed weights in the MPP system, although these were slightly lower than those observed in NPP. Under NF treatment, seed weights were notably reduced, particularly in the MPP system, suggesting that nutrient competition between maize and pigeon pea limits grain filling and reduces seed size.

3.3.3. Total grain yield

Grain yield reflects the combined effects of cob development and seed weight. In the MPP system, the highest grain yield was recorded during the major season under FR treatment (6.47 tons/ha), slightly exceeding that of the NPP system under the same conditions (5.82 tons/ha, Table 3). This suggests that intercropping under high nutrient availability can match or even surpass sole cropping in productivity due to complementary interactions between crops. However, under NF treatment, grain yield in the MPP system (3.85 tons/ha in the major season) was lower than in NPP (4.35 tons/ha), highlighting the greater impact of resource competition in the absence of fertilizer (Table 3).

3.4. LER

The LER was calculated using Equation III to evaluate the productivity benefits of intercropping maize and pigeon pea compared to their sole cropping systems:

- $Y_m I$: maize yield under intercropping (tons/ha) = 3.93
- $Y_m S$: maize yield under sole cropping (tons/ha) = 4.30
- $Y_p I$: pigeon pea yield under intercropping (tons/ha) = 0.25
- $Y_p S$: pigeon pea yield under sole cropping (tons/ha) = 0.79

$$LER = \frac{Y_m I}{Y_m S} + \frac{Y_p I}{Y_p S} = \frac{3.93}{4.30} + \frac{0.25}{0.79} = 1.23$$

An LER value of 1.23 indicates a productivity advantage for the intercropping system. Since LER values greater

than one indicate higher combined yields in intercropping compared to sole cropping, this finding highlights a more efficient use of land resources. The increased combined yield suggests enhanced resource utilization, where maize and pigeon peas benefit from shared resources, such as light, water, and nutrients. This synergy contributes to increased overall productivity in the intercropping system.

In addition, the complementary growth patterns of maize and pigeon peas in the intercropping system may contribute to the observed yield advantage. Pigeon pea, being taller, can provide partial shade during the early stages of maize growth, which helps suppress weed growth and supports soil moisture conservation. In addition, as a leguminous plant, pigeon pea also enhances soil fertility by fixing atmospheric nitrogen, thereby benefiting maize development. The higher LER value suggests that intercropping can offer improved economic returns for farmers by increasing yield per unit area, thereby enhancing overall profitability. This system also supports environmental sustainability through increased biodiversity, reduced dependency on chemical inputs, and improved soil health. Overall, an LER of 1.23 indicates a 23% advantage of intercropping maize and pigeon peas over sole cropping in terms of land-use efficiency, complementary resource utilization, economic benefits, and environmental sustainability.

3.5. Soil physicochemical properties at the Fumesua study site

Table 4 shows the physicochemical properties of soil at the Fumesua study site analyzed at the initial stage in 2022 and after 2 years of cropping under different treatments: pigeon pea alley cropping and NPP cropping. The results showed distinct variations in soil properties across depths and treatments. At the initial stage, the topsoil (0 – 20 cm) had a pH of 6.50, indicating slightly acidic conditions, with 0.26% nitrogen (N) and 49.15 mg/kg phosphorus (P). Potassium (K) measured 0.21 cmol (+)/kg, while magnesium (Mg) and calcium (Ca) measured 0.69 cmol (+)/kg and 1.35 cmol (+)/kg, respectively. Organic carbon (OC) accounted for 1.11%, and organic matter (OM) comprised 1.98%. The soil texture was loamy sand, consisting of 82.10% sand, 8.89% clay, and 9.01% silt. At a depth of 20 – 40 cm, the soil pH decreased to 6.02, accompanied by a decline in N (0.13%) and P (33.04 mg/kg). The texture at this depth was sandy loam, with a slightly lower sand content (73.43 %) and higher clay (10.88 %) and silt (15.69%) contents.

In addition, soil properties in the pigeon pea alley cropping after 2 years showed that the 0 – 20 cm layer exhibits increased N (0.39%) and P (48.42 mg/kg) levels compared to the initial stage. Both Ca and Mg levels

Table 4. Physicochemical properties of soil at the study site in Fumesua during the initial stage in 2022 and after 2 years of cropping

Soil depth (cm)	Chemical properties						Physical properties					
	pH	N (%)	P (mg/kg)	K (cmol (+)/kg)	Mg (cmol (+)/kg)	Ca (cmol (+)/kg)	OC (%)	OM (%)	Sand (%)	Clay (%)	Silt (%)	Texture class
Initial soil parameters												
0 – 20	6.50	0.26	49.15	0.21	0.69	1.35	1.11	1.98	82.10	8.89	9.01	Loamy sand
20 – 40	6.02	0.13	33.04	0.15	0.67	0.82	0.75	1.21	73.43	10.88	15.69	Sandy loam
Soil parameters in the pigeon pea alley after 2 years												
0 – 20	6.37	0.39	48.42	0.20	0.80	2.25	2.11	3.11	81.99	8.99	9.02	Loamy sand
20 – 40	6.22	0.45	30.94	0.21	0.80	1.12	1.75	2.25	73.00	11.00	16.00	Sandy loam
Soil parameters in the sole maize after 2 years												
0 – 20	6.48	0.26	48.05	0.23	0.59	1.25	0.81	0.98	81.90	8.90	9.20	Loamy sand
20 – 40	6.12	0.13	33.34	0.15	0.55	0.83	0.80	0.21	74.03	10.80	15.17	Sandy loam

Abbreviations: Ca: Calcium; K: Potassium; Mg: Magnesium; N: Nitrogen; OC: Organic carbon; OM: Organic matter; P: Phosphorus.

increased significantly to 2.25 cmol (+)/kg and 0.80 cmol (+)/kg, respectively. Moreover, OC and OM improved to 2.11% and 3.11%, respectively, suggesting enhanced soil fertility under pigeon pea cropping. At a depth of 20 – 40 cm, the concentrations of N and P were 0.45% and 30.94 mg/kg, respectively. Ca slightly decreased to 1.12 cmol (+)/kg, while Mg remained stable. Soil texture remained sandy loam, with 73% sand, 11% clay, and 16% silt.

The soil properties in the NPP system after 2 years at the 0 – 20 cm depth showed that N remains constant at 0.26%, matching the initial soil values, while P slightly decreased to 48.05 mg/kg. Ca measured 1.25 cmol (+)/kg and OM declined to 0.98%, both lower than in the pigeon pea alley cropping, suggesting reduced organic input from maize. At a depth of 20 – 40 cm, N and P levels were 0.13% and 33.34 mg/kg, respectively, comparable to the initial soil values. Ca and Mg levels were slightly lower than those in the pigeon pea alley cropping, while OM content remained low at 0.21%.

3.6. Economic analysis

The benefit–cost ratio (BCR) was employed for the economic analysis. The MPP cropping systems were compared to NPP system under varying fertilizer levels to assess resource optimization and profitability. BCR, a key indicator of economic advantage, varied across cropping systems and fertilizer applications, reflecting the relationship between input costs and yield benefits

(Table 5). In the MPP cropping system, the BCR under NF treatment was 2.16, demonstrating economic viability even under minimal input conditions. This suggests that incorporating pigeon pea, a nitrogen-fixing legume, can reduce the need for chemical fertilizers by naturally enhancing soil fertility. Under the HR treatment, the BCR slightly decreased to 1.91, indicating that the additional fertilizer cost does not proportionally increase economic returns. However, with FR fertilizer application, the BCR improved significantly to 2.81, highlighting the potential for maximized profitability when input levels are optimized (Table 5).

In contrast, the NPP system presented a slightly different trends. Under the NF treatment, the BCR was 2.04, demonstrating moderate economic returns with low input (Table 5). Interestingly, the BCR increased to 2.81 under the HR treatment, similar to the highest return observed in the MPP system. This suggests that maize responds well to moderate fertilizer application, possibly due to the alleviation of nutrient constraints that limit growth and yield. However, under FR treatment application, the BCR was reduced to 2.37, reflecting diminishing returns at higher input levels (Table 5). This indicates that the NPP system is less efficient in translating additional fertilizer into economic benefits than the MPP system (Table 5).

4. Discussion

The study highlights the crucial role of MPP intercropping systems in addressing the productivity, sustainability,

Table 5. Partial budgeting between maize–pigeon pea intercrop and sole maize systems under four different fertilization application rates averaged for the cropping seasons

Cropping system	Maize–pigeon pea			Sole maize		
	NF	HR	FR	NF	HR	FR
Maize average yields (kg/ha)	3,165	3,426	5,198	3,174	4,891	4,828
Adjusted maize yield*	2,849	3,083	4,678	2,857	4,402	4,345
Gross benefit of maize (GHC/ha)	28,485	30,834	46,782	28,566	44,019	43,452
Pigeon pea average yields (kg/ha)	250	250	250	-	-	-
Adjusted pigeon pea yield*	225	225	225	-	-	-
Gross benefit of pigeon pea (GHC/ha)	1,575	1,575	1,575	-	-	-
Gross benefit of the cropping system	30,060	32,409	48,357	28,566	44,019	43,452
Cost of pigeon pea establishment (GHC/ha)	800	800	800	-	-	-
Cost of harvesting pigeon pea (GHC/ha)	400	400	400	-	-	-
Cost of pruning and spreading pigeon pea biomass (GHC/ha)	400	400	400	-	-	-
Cost of chemical fertilizer (GHC/ha)	-	1,250	2,500	-	1,250	2,500
Labor cost for the application of fertilizer (GHC/ha)	-	400	700	-	900	1,000
Land clearing (GHC/ha)	3,000	3,000	3,000	3,000	3,000	3,000
Cost of maize seed (GHC)	200	200	200	300	300	300
Labor cost of planting (C/ha)	1,200	1,200	1,200	1,400	1,400	1,400
Cost of weeding (GHC/ha)	1,500	1,500	1,500	2,200	2,200	2,200
Harvesting cost (GHC/ha)	2,000	2,000	2,000	2,500	2,500	2,500
Total costs that vary	8,700	10,350	11,900	9,400	11,550	12,900
Total cost of the system	9,500	11,150	12,700	9,400	11,550	12,900
Net benefit	20,560	21,259	35,657	19,166	32,469	30,552
Benefit–cost/ratio	2.16	1.91	2.81	2.04	2.81	2.37

Note: Asterisk (*) represents 10% of maize average yield against inflation and price volatilities.

Abbreviations: FR: Full rate of recommended fertilizer; GHC/: Ghana Cedi; HR: Half rate of recommended fertilizer; NF: No fertilizer.

and resilience challenges faced by smallholder farmers in Ghana. The findings indicate that intercropping systems are more productive and sustainable than monocultures, as they efficiently utilize resources and provide ecological benefits.^{22,23} The inclusion of pigeon pea biomass significantly enhanced soil nutrient availability and improved maize growth, yield components, and total grain yield. These results support previous studies demonstrating that pigeon pea contributes to soil fertility through nitrogen fixation and the incorporation of OM.^{24,25}

The study demonstrates that maize yields in intercropping systems are comparable to those in sole cropping under FR treatment and exceed them under moderate (HR) and low fertilizer input (NF) conditions. These findings support the idea that pigeon pea biomass can supplement and partially replace inorganic fertilizers without compromising yields.^{4,12,23} This finding is particularly relevant for smallholder farmers, who often face challenges due to the high cost and limited availability of chemical fertilizers.^{13,26} Furthermore, the strong

performance of intercropping systems under varying environmental conditions highlights their resilience, making them well-suited for areas with erratic rainfall and poor soil fertility.¹⁵

The high maize yields recorded during the major season, likely due to increased rainfall, highlight the critical influence of environmental conditions on cropping system performance. While monoculture systems such as NPP demonstrated high productivity under optimal fertilizer input, they exhibited limited resilience under nutrient constraints and seasonal variability. In contrast, the intercropping system maintained yield stability, suggesting that the ecological and functional complementarities between maize and pigeon peas contribute to enhanced system resilience.²⁷ In addition, intercropping systems offer significant economic advantages. The reduced reliance on chemical fertilizers lowered production costs, thereby enhancing profitability and accessibility for resource-constrained farmers.²⁸ Pigeon pea grains also serve as a valuable dietary supplement for farm households,

contributing to improved food security and nutritional diversity.²⁹ These findings align with previous studies that highlight the role of legumes in enhancing soil fertility, reducing chemical input dependency, and improving crop profitability.^{14,30}

Beyond economic benefits, intercropping systems also contribute significantly to ecological sustainability. Pigeon pea enhances nitrogen fixation, facilitates biomass recycling, and promotes soil carbon sequestration, all of which support improved soil health and long-term productivity.^{11,16,31,32} These ecological benefits align with the principles of sustainable agriculture, positioning MPP intercropping as a promising strategy for climate-resilient farming systems.³³ However, the scope of this study is limited to a single agroecological zone, which may limit the applicability of the findings. Further research is needed to evaluate the system's performance across diverse regions. In addition, although economic benefits were inferred, detailed economic analyses incorporating BCRs and profitability metrics would provide a more comprehensive understanding.¹⁰ The observed trade-offs between productivity and sustainability highlight the need for careful optimization of planting densities, row spacing, and fertilizer application rates to maximize the system's overall benefits.³⁴

Farmers should consider integrating pigeon peas into maize cropping systems to reduce fertilizer costs, enhance soil fertility, and increase resilience to environmental stresses.³⁵ Future studies should focus on identifying optimal planting densities, row spacing, and variety selection for MPP intercropping across diverse agroecological zones. In addition, policymakers are encouraged to support the adoption of intercropping systems through targeted subsidies, extension services, and farmer training programs. The findings highlight a strategic trade-off: while monocultures may maximize yields under optimal conditions, they lack resilience, whereas intercropping systems offer a balanced approach – combining stable productivity, ecological benefits, and resilience under variable conditions.²⁷ Integrating pigeon peas into maize cropping systems can therefore support sustainable intensification, reduce environmental impacts, and strengthen food security. This study illustrates that pigeon peas can serve as a vital resource for farming communities, thriving in challenging environments while providing multiple benefits.^{36,37}

In summary, pigeon pea alley cropping enhanced soil fertility by increasing levels of N, P, OC, and Ca. NPP cropping system did not significantly enhance soil nutrients, showing values similar to those of the initial soil properties. These findings highlight the potential of pigeon

pea alley cropping in improving soil health and maintaining fertility over time. MPP intercropping systems represent a promising approach for the sustainable intensification of agriculture, effectively integrating productivity, resilience, and ecological sustainability. They offer a practical solution for smallholder farmers in Ghana and comparable settings, helping to address critical challenges such as declining soil fertility, climate variability, and limited access to inputs. Future research and policy support will be essential to achieving the full potential of these systems in ensuring food security and environmental sustainability.

5. Conclusion

An ISFM approach incorporating legume agroforestry trees, such as pigeon peas, offers a promising solution for sustainable maize production. This approach addresses the challenge of maintaining soil fertility, which has contributed to declining maize yields. Pigeon pea not only provides reliable biomass and shade that conserve soil moisture but also helps suppress weeds. These advantages of the MPP cropping systems enhance resource use efficiency and maize productivity. Therefore, ISFM – planting maize with pigeon pea combined with half the recommended fertilizer rate (125 kg/ha of 15-15-15 N-P₂O₅-K₂O + 125 kg/ha of SoA) – could be a viable strategy for sustainable maize production on continuously cropped fields. However, further research is needed to evaluate whether fertilizer rates can be reduced even further without compromising maize productivity and economic returns. This is crucial for sustaining maize production among smallholder farmers amid climate change, thereby contributing to improved food security.

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Conflict of interest

The authors declare no conflicts of interest.

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