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Integrated Use of Pigeon Pea Residues and Mineral Fertilizers Enhances Rainfed Rice Productivity and Soil Health in a Humid Forest Zone

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Abstract

Sustainable intensification of rainfed rice systems in sub-Saharan Africa is constrained by low soil fertility and limited access to mineral fertilizers. Integrated nutrient management that combines organic and mineral sources offers a promising pathway to enhance productivity and soil health. A field experiment was conducted in Nkolbisson, Cameroon, to evaluate the effects of pigeon pea (*Cajanus cajan* L.) biomass and mineral fertilizers on the growth, yield, and soil properties of rainfed rice (variety NERICA 8). The experiment employed a randomized complete block design with four treatments: control (T0), NPK only (T1, 200 kg ha^{-1}), NPK + pigeon pea biomass (T2, 200 kg ha^{-1} NPK + 17 t ha^{-1} biomass), and NPK + urea (T3, 200 kg ha^{-1} NPK + 100 kg ha^{-1} urea). Results showed that T2 significantly (p<0.05p<0.05) improved plant height, tiller number, and leaf nitrogen status compared to other treatments. Grain yield under T2 reached 5.06 t ha^{-1}, a 40.5% increase over NPK alone (3.99 t ha^{-1}) and 28.5% higher than NPK + urea (4.39 t ha^{-1}). The integrated treatment also enhanced key yield components: panicle density (85 m^{-2}), grains per panicle (58.4), and 1000-grain weight (27.0 g). Post-harvest soil analysis indicated that T2 significantly increased available phosphorus (+29.8%) and exchangeable potassium (+37.1%), while maintaining a more favorable C/N ratio (9:1) than mineral-only treatments. Economic analysis revealed the highest gross value added under T2 (1,310,500 FCFA ha^{-1}), despite higher initial costs. We conclude that integrating pigeon pea residues with reduced-dose NPK fertilizer is an agronomically effective and economically viable strategy for enhancing rainfed rice productivity and soil fertility in humid tropical Africa. This practice supports sustainable intensification by improving nutrient use efficiency, building soil organic matter, and reducing dependency on external mineral inputs.

Keywords: *Cajanus cajan*; Integrated Soil Fertility Management; Nutrient Use Efficiency; Soil Organic Carbon; Sustainable Intensification; Upland Rice; West Africa

Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the global population and the second most consumed cereal after wheat [7]. In sub-Saharan Africa (SSA), rice consumption has surged at an annual rate of 5.5%—the highest in the world—driven by population growth, urbanization, and shifting dietary preferences [29]. However, regional production remains insufficient, forcing many African nations to rely heavily on costly imports to meet demand. In Cameroon, rice imports currently satisfy over 50% of domestic consumption, representing a significant drain on foreign reserves and exposing the country to volatile international market prices [19].

Rainfed upland rice systems, which rely solely on rainfall and cover approximately 40% of the rice area in SSA, are particularly important for food security in humid forest and savanna zones [28]. These systems are predominantly managed by smallholder farmers with limited access to irrigation and external inputs. While offering a lower-risk alternative to irrigated systems, rainfed rice yields remain stubbornly low, averaging only 1.5–2.5 t ha^{-1}, far below the genetic potential of improved varieties like NERICA (*New Rice for Africa*) which can achieve 5–7 t ha^{-1} under optimal conditions [25]. The primary biophysical constraint to productivity is the rapid depletion of soil fertility, a consequence of continuous cropping with minimal nutrient replenishment on inherently poor, acidic tropical soils [36].

Conventional soil fertility management in these systems has historically relied on mineral fertilizers. While effective in the short term, their sole application presents multiple challenges:

high and volatile costs limit accessibility for resource-poor farmers; nutrient use efficiency is often low due to leaching and fixation; and continuous use can exacerbate soil acidification and reduce organic matter [4]. Moreover, the environmental footprint of fertilizer manufacturing and the risk of eutrophication from nutrient runoff underscore the need for more sustainable nutrient management paradigms [41].

Integrated Soil Fertility Management (ISFM)—the combined application of mineral and organic nutrient sources—has emerged as a cornerstone strategy for sustainable agricultural intensification in SSA [35]. ISFM aims to enhance nutrient use efficiency, build soil organic carbon (SOC), and improve system resilience. Among organic resources, leguminous green manures and crop residues hold particular promise due to their ability to biologically fix atmospheric nitrogen (N) and recycle other nutrients. Pigeon pea (*Cajanus cajan* L. Millsp.) is a multi-purpose legume well-adapted to marginal environments; it is drought-tolerant, has a deep rooting system that captures leached nutrients, and can solubilize phosphorus (P) from fixed soil pools through root exudates [20, 31]. Its biomass, rich in N and other nutrients, can serve as a potent organic amendment, potentially reducing the required dosage of mineral fertilizers while improving soil structure and microbial activity [6].

Recent evidence from across SSA demonstrates the agronomic benefits of integrating legume residues. Studies in Malawi and Tanzania have shown that pigeon pea–maize rotations increase subsequent cereal yields by 30–50% and improve soil water retention [18]. In West Africa, the use of woody legume biomass (e.g., *Gliricidia sepium*) in agroforestry systems has significantly boosted maize and sorghum productivity [13]. However, research focusing specifically on the integration of pigeon pea residues with mineral fertilizers for rainfed rice systems in the humid forest zones of Central Africa remains scarce. Most existing studies have evaluated pigeon pea in rotation, not as a direct, incorporated amendment within the same cropping season—a practice that could offer immediate fertility benefits without delaying rice planting [21].

This study was therefore designed to address this knowledge gap. We hypothesize that the integrated application of pigeon pea biomass and reduced-dose mineral NPK fertilizer will (i) significantly improve the growth and yield of rainfed rice, (ii) enhance key soil fertility parameters (particularly N, P, and SOC), and (iii) offer greater economic returns than sole mineral fertilization. The specific objectives wereto:

1. Quantify the effects of combined pigeon pea biomass and mineral fertilizers on rice growth parameters and yield components.
2. Assess the post-harvest impact of these treatments on soil chemical properties.
3. Evaluate the economic viability of the different fertilization strategies.

By testing these hypotheses in the humid forest zone of Cameroon, this research aims to contribute to the development of locally adapted, profitable, and sustainable nutrient management recommendations for smallholder rice farmers, thereby supporting efforts to enhance food security and agricultural sustainability in the region.

Materials and Methods

Study Site and Soil Characteristics

The study was conducted during the 2024 cropping season (March–July) in Nkolbisson (3°51'55.3"N, 11°27'38"E, altitude 500–850 m), located in the Centre Region of Cameroon. The site experiences a humid tropical climate with a bimodal rainfall pattern, characterized by two rainy seasons (March–June and September–November) and a mean annual temperature of 25°C. The average annual rainfall is approximately 1,600 mm.

Prior to experimentation, composite soil samples (0–30 cm depth) were collected from three blocks across the experimental area using a soil auger. Samples were air-dried, sieved (<2 mm), and analyzed for key physicochemical properties following standard methods [24]. Soil texture was determined using the pipette method [5]. Soil pH was measured in a 1:2.5 soil–water suspension. Organic carbon (OC) was analyzed using the Walkley–Black method [38]. Total nitrogen (N) was determined by Kjeldahl digestion [2]. Available phosphorus (P) was extracted using the Bray-II method [1]. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1 N ammonium acetate (pH 7.0) and measured by atomic absorption spectrophotometry (Ca, Mg) and flame photometry (K, Na). Cation exchange capacity (CEC) was calculated as the sum of exchangeable bases and exchangeable acidity.

Plant Materials and Fertilizers

The rice variety used was *NERICA 8* (*Oryza sativa* L.), an early-maturing, drought-tolerant upland rice variety developed by the Africa Rice Center.

- **Fertilizers includedMineral fertilizers:** NPK (20-10-10) and urea (46% N), sourced locally.
- **Organic amendment:** Dry biomass of pigeon pea (*Cajanus cajan* L. Millsp.) consisting of leaves and pods collected after threshing from fields in Bertoua, Cameroon. The biomass was air-dried, chopped into small pieces (<5 cm), and analyzed for total N, P, K, Ca, and Mg (Table 2 in original report).

Experimental Design and Treatments

A randomized complete block design (RCBD) with three replications was employed. The experimental unit size was 3 m × 3 m (9 m^2), with 1 m spacing between plots and blocks.

- Four treatments were evaluated: T0: Control (no fertilizer)
- T1: 200 kg ha^{-1} NPK (20-10-10)
- T2: 200 kg ha^{-1} NPK (20-10-10) + 17 t ha^{-1} pigeon pea biomass
- T3: 200 kg ha^{-1} NPK (20-10-10) + 100 kg ha^{-1} urea (split-applied: 50 kg ha^{-1} at panicle initiation and 50 kg ha^{-1} at flowering)

Pigeon pea biomass was incorporated into the soil four days before sowing at a rate of 15.3 kg per plot, equivalent to 17 t ha^{-1}. NPK was applied basally at 14 days after sowing (DAS). Urea was applied in two equal splits at 60 and 75 DAS.

Crop Management

Land preparation involved manual clearing, hoeing, and ridging. Rice was shown on 20 March 2024 at a spacing of 25 cm × 25 cm with 5 seeds per hill, later thinned to 3 plants per hill at 14 DAS. Weeding was done manually at 30, 45, and 60 DAS. No irrigation was applied; the crop relied solely on rainfall.

Data Collection

Growth Paramete

- **Plant height (cm):** Measured from ground level to the tip of

Table 1: Initial physicochemical properties of the soil (0–30 cm depth) at the experimental site in Nkolbisson, Cameroon (mean ± standard deviation, n = 3).

Parameter	Block 1	Block 2	Block 3	Mean ± SD
pH (H_2O)	4.6	4.2	4.3	4.4 ± 0.2
Organic C (%)	3.56	3.90	2.19	3.23 ± 0.9
Organic Matter (%)	6.13	6.72	4.77	5.57 ± 1.0
Total N (g kg^{-1})	1.63	1.85	1.21	1.56 ± 0.3
C/N Ratio	22	21	17	20 ± 3
Avail. P-Bray II (mg kg^{-1})	15.69	14.36	15.82	15.29 ± 0.8
Exch. K ($cmol^{+}$ kg^{-1})	0.35	0.51	0.20	0.35 ± 0.2
CEC ($cmol^{+}$ kg^{-1})	14.17	17.14	20.00	17.10 ± 3.0
Base Saturation (%)	22	27	28	26 ± 3
Texture (%)				
Sand	37.0	40.5	39.0	38.8 ± 1.8
Silt	26.0	13.5	20.5	20.0 ± 6.3
Clay	37.0	46.0	40.5	41.2 ± 4.6

the longest leaf on 20 randomly selected plants per plot at 30, 45, 60, and 75 DAS.

- **Tiller count:** Number of productive tillers per plant recorded on the same plants and dates.
- **Leaf color index:** Assessed using the Standard Evaluation System for Rice leaf color chart (LCC, 1–7 scale) at 30, 45, 60, and 75 DAS (IRRI, 1988).

Yield and Yield Components

At physiological maturity (≈110 DAS), the following were determined:

- **Panicle number per m²:** Counted in three 1 m² quadrats per plot.
- **Grains per panicle:** Average from 10 randomly selected panicles per plot.
- **Grain filling percentage:** Calculated as:

$$\text{Grain filling (\%)} = \left(\frac{\text{Number of filled grains}}{\text{Total grains}}\right) \times 100$$

- **1000-grain weight (g):** Determined from three random samples of 1000 grains per plot, adjusted to 14% moisture content.
- **Grain yield (t ha^{-1}):** Harvested from the net plot area, threshed, sun-dried, and weighed. Yield was adjusted to 14% moisture and extrapolated to per hectare basis.

Soil Sampling and Analysis Post-Harvest

After harvest, soil samples (0–30 cm) were collected from each treatment, composited per replicate, and analyzed using the same methods as pre-planting to assess treatment effects on soil properties.

Economic Analysis

A partial budget analysis was performed to compare the economic viability of treatments. The following were calculated per hectare basis:

Consumption Intermediary (CI) = Cost of inputs + Cost of labor

Gross Product (GP) = Yield (kg ha^{-1}) × Market price (FCFA kg^{-1})

Gross Value Added (GVA) = *GP - CI*

Input costs included seeds, fertilizers, and biomass. Labor costs covered land preparation, sowing, weeding, and harvesting. The local market price of paddy rice was set at 1,000 FCFA kg^{-1}.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using R 4.5.1. Treatment means were separated using Tukey's HSD test at $p \leq 0.05$. Pearson's correlation analysis was conducted to examine relationships between yield components. Principal component analysis (PCA) was performed to visualize treatment effects on growth, yield, and soil parameters.

Results

Initial Soil and Pigeon Pea Biomass Characteristics

The soil at the experimental site in Nkolbisson was classified as loamy sand clay texture with mean values of 38.8% sand, 20.0% silt, and 41.2% clay (Table 1). Initial soil analysis revealed acidic conditions (pH-H_2O: 4.4 ± 0.2) and moderate organic matter content (5.57 ± 1.0%). Total nitrogen (1.56 ± 0.3 g kg^{-1}) and available phosphorus (15.29 ± 0.8 mg kg^{-1}) were classified as moderate, while exchangeable potassium was low (0.35 ± 0.2 $cmol^{+}$ kg^{-1}). The cation exchange capacity (CEC) was 17.10 ± 3.0 $cmol^{+}$ kg^{-1} with a base saturation of 26 ± 3%, indicating moderate nutrient retention capacity. The C/N ratio of 20 ± 3 suggested moderate organic matter quality.

The pigeon pea (*Cajanus cajan*) biomass used as organic amendment showed high nutrient concentrations, particularly in nitrogen (25.10 g kg^{-1} or 2.51%) and potassium (5235.78 mg kg^{-1}) (Table 2). The phosphorus content was 968.16 mg kg^{-1}, calcium

Table 2: Nutrient composition of pigeon pea (*Cajanus cajan*) biomass used as organic amendment in the study.

Nutrient	Concentration	Unit
N	25.10	g kg^{-1}
N	2.51	%
P	968.16	mg kg^{-1}
K	5235.78	mg kg^{-1}
Ca	4240.00	mg kg^{-1}
Mg	2721.60	mg kg^{-1}
Na	134.79	mg kg^{-1}

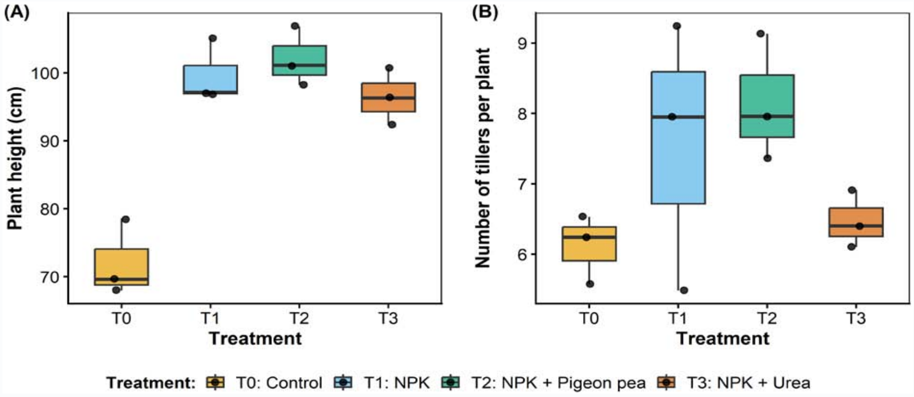

Figure 1: Growth parameters of rainfed rice (NERICA 8) as influenced by different fertilization treatments at Nkolbisson, Cameroon. (A) Plant height (cm) at 75 days after sowing (DAS). (B) Number of tillers per plant at 75 DAS. Treatments: T0 = Control (no fertilizer); T1 = NPK (20-10-10, 200 kg ha^{-1}); T2 = NPK (200 kg ha^{-1}) + pigeon pea (Cajanus cajan) biomass (17 t ha^{-1}); T3 = NPK (200 kg ha^{-1}) + urea (100 kg ha^{-1}). Boxes show interquartile ranges with medians; points represent individual replicates (n = 3). Different letters above boxes indicate significant differences (p ≤ 0.05, Tukey's HSD test).

4240.00 mg kg^{-1}, magnesium 2721.60 mg kg^{-1}, and sodium 134.79 mg kg^{-1}, indicating its potential as a comprehensive organic fertilizer and soil conditioner.

Growth Parameters

Plant Height: Plant height was significantly influenced ($p < 0.05$) by fertilization treatments from 45 days after sowing (DAS) onward (Figure 1A). At 75 DAS, the tallest plants were recorded under T2 (104.53 ± 12.78 cm), representing a 47.8% increase over the control (T0: 70.75 ± 16.55 cm). Treatments T1 (96.45 ± 14.27 cm) and T3 (94.50 ± 7.09 cm) showed intermediate values, both significantly taller than T0 but shorter than T2. Statistical analysis revealed significant differences among all treatments except between T1 and T3 at this growth stage.

Tiller Dynamics: Tiller number increased progressively until 75 DAS, with significant treatment effects observed from 45 DAS (Figure 1B). At maturity (75 DAS), T2 produced the highest number of tillers per plant (8.43 ± 3.83), significantly ($p < 0.05$) higher than T0 (6.13 ± 5.57). Treatments T1 (7.45 ± 6.31) and T3 (7.13 ± 3.29) showed intermediate tiller counts that were not statistically different from either T0 or T2. The integrated treatment (T2) promoted more stable and productive tillering throughout the growth period compared to mineral-only treatments.

Leaf Color Index (Nitrogen Status)

Leaf color chart (LCC) scores, indicating plant nitrogen status, showed clear temporal and treatment-related patterns (Figure 2). From 30 to 75 DAS, all fertilized treatments maintained higher LCC scores than the control, with T2 consistently showing the darkest green leaves. At 75 DAS, T2 achieved a mean LCC score of 6.0 (dark green), compared to 5.2 for T1, 5.5 for T3, and 4.2 for T0. The sustained high LCC scores in T2 throughout the growing season reflected better and more prolonged nitrogen availability from the organic-mineral combination.

Yield and Yield Components

Panicle Density and Grain Characteristics: Panicle density per m^2 was highest under T2 (85 panicles m^{-2}), significantly ($p < 0.05$) surpassing T1 (65 panicles m^{-2}), T3 (70 panicles m^{-2}), and T0 (45 panicles m^{-2}) (Figure 3A). The number of grains per panicle followed a similar trend, with T2 yielding the highest count (58.35 ± 13.23 grains), significantly greater than T0 (30.23 ± 2.10) and T1 (40.22 ± 2.60) (Table 3).

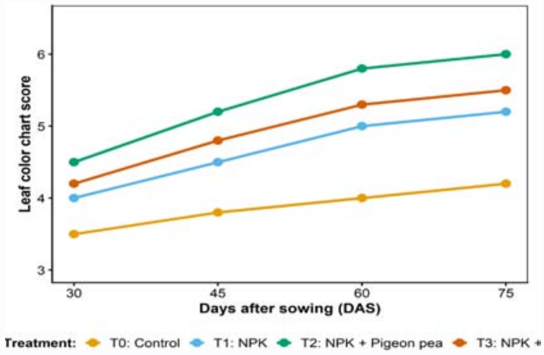

Figure 2: Temporal dynamics of leaf color chart (LCC) scores indicating nitrogen status of rice plants under different fertilization treatments. LCC scores range from 1 (very light green, severe N deficiency) to 7 (very dark green, possible N excess). Values are means of three replicates. Treatments as described in Figure 1. Error bars represent ± standard error.

Grain Filling and 1000-Grain Weight: The percentage of filled grains was significantly improved by organic-mineral integration (Figure 3B). T2 achieved near-complete grain filling (99.2 ± 0.8%), significantly ($p < 0.05$) higher than all other treatments. T3 showed intermediate performance (88.8 ± 9.0%), followed by T1 (78.6 ± 10.5%) and T0 (61.5 ± 5.0%).

The 1000-grain weight showed similar treatment effects (Figure 3C, Table 3). T2 produced the heaviest grains (27.0 ± 2.0 g), significantly heavier than T0 (18.0 ± 1.2 g) and T1 (22.0 ± 1.5 g), but not statistically different from T3 (25.0 ± 1.8 g). This represented a 50% increase in grain weight compared to the control.

Grain Yield: Grain yield was significantly ($p < 0.05$) influenced by fertilization treatments (Figure 4). The highest yield was obtained with T2 (5.06 t ha^{-1}), representing a 40.5% increase over T1 (3.99 t ha^{-1}), a 28.5% increase over T3 (4.39 t ha^{-1}), and a 40.6% increase over T0 (3.60 t ha^{-1}). All fertilized treatments significantly outyielded the control, with the organic-mineral combination (T2) showing clear

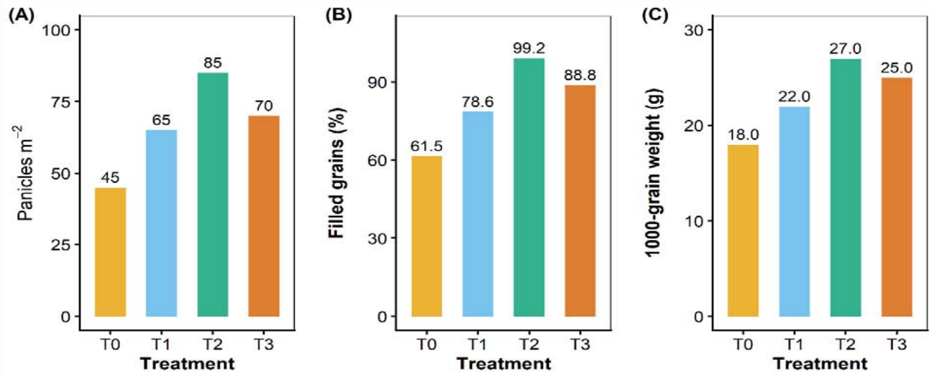

Figure 3: Yield components of rainfed rice under different fertilization treatments. (A) Panicle density per square meter. (B) Percentage of filled grains. (C) Thousand-grain weight (g). Treatments as described in Figure 1. Bars represent means ± standard error (n = 3). Different letters above bars indicate significant differences among treatments ($p \leq 0.05$, Tukey's HSD test).

Table 3: Effect of fertilization treatments on yield components of rainfed rice (NERICA 8) at Nkolbisson, Cameroon.

Treatment	Grains Panicle^{-1}	Filled Grains (%)	1000-Grain Weight (g)
T0	30.23 ± 2.10^{a}	61.5 ± 5.0^{a}	18.0 ± 1.2^{a}
T1	40.22 ± 2.60^{a}	78.6 ± 10.5^{b}	22.0 ± 1.5^{b}
T2	58.35 ± 13.23^{b}	99.2 ± 0.8^{c}	27.0 ± 2.0^{c}
T3	47.03 ± 3.36^{b}	88.8 ± 9.0^{b}	25.0 ± 1.8^{bc}

superiority over mineral-only treatments.

Principal Component Analysis

Principal component analysis of growth and yield parameters revealed clear separation among treatments (Figure 5). The first two principal components explained 78.3% of the total variance (PC1: 58.1%, PC2: 20.2%). Treatment T2 was distinctly separated in the positive quadrant of PC1, strongly associated with yield-related variables: grain yield, panicles per m², grains per panicle, and 1000-grain weight. T0 clustered in the negative quadrant, associated with low values of all measured parameters. T1 and T3 showed intermediate positions, with T3 slightly closer to T2 due to better performance in grain-related traits.

Post-Harvest Soil Properties

Fertilization significantly altered key soil chemical properties following rice cultivation (Table 4). Soil pH remained unchanged across treatments ($p > 0.05$), maintaining acidic conditions (pH 4.1-4.6). Soil organic carbon (SOC) showed significant treatment effects, with T2 maintaining the highest SOC (2.13 ± 0.61%), though all treatments showed reductions from initial levels.

Total nitrogen increased in all fertilized plots, with the highest increment under T3 (0.312 ± 0.04 g kg^{-1}), likely reflecting immediate N availability from urea. However, the C/N ratio narrowed most dramatically under T2 (from initial 20 to 9), indicating enhanced N mineralization activity associated with pigeon pea incorporation.

Available phosphorus showed the most striking treatment effect ($p < 0.001$), with T2 significantly higher (19.84 ± 0.42 mg kg^{-1}) than all other treatments, demonstrating the P-mobilizing effect of pigeon pea residues. Exchangeable potassium was also highest in T2 (0.48 ± 0.0 cmol^{+} kg^{-1}), suggesting reduced K leaching or improved recycling through organic amendment.

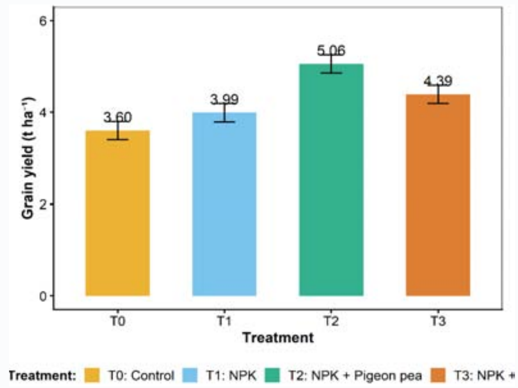

Figure 4: Grain yield (t ha^{-1}, at 14% moisture) of rainfed rice as affected by fertilization treatments. Treatments as described in Figure 1. Bars represent means with error bars showing ± standard error (n = 3). Different letters above bars indicate significant differences ($p \leq 0.05$, ANOVA followed by Tukey's HSD test).

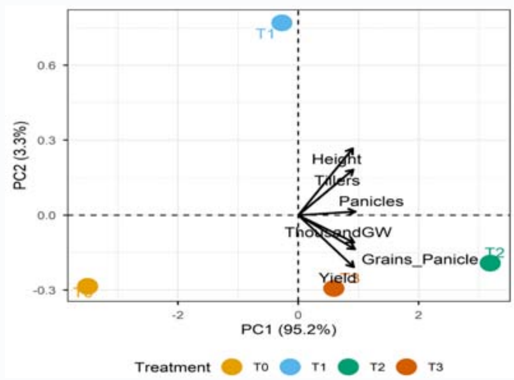

Figure 5: Principal component analysis (PCA) biplot of growth and yield parameters of rainfed rice under different fertilization treatments. Treatments: T0 (●), T1 (▲), T2 (♦), T3 (■). Variables: Height = plant height; Tillers = number of tillers; Panicles = panicles per m²; GrainPan = grains per panicle; TGW = thousand-grain weight; Yield = grain yield. PCI and PC2 explained 58.1% and 20.2% of total variance, respectively. Treatment T2 clusters separately due to superior performance in yield-related variables.

Economic Analysis

Partial budget analysis revealed clear economic advantages of the integrated fertilization approach (Table 5). Although T2 had

Table 4: Selected soil chemical properties (0–30 cm) after rice harvest as influenced by fertilization treatments.

Treatment	pH (H_2O)	SOC (%)	Total N (g kg^{-1})	C/N	Avail. P (mg kg^{-1})	Exch. K (cmol+ kg^{-1})
Initial	4.4	3.23	0.156	20	15.29	0.35
T0	4.3 ± 0.3	1.88 ± 0.78^a	0.188 ± 0.02^a	10 ± 15.6^a	10.14 ± 0.13^a	0.28 ± 0.0^a
T1	4.3 ± 0.3	1.88 ± 0.78^a	0.188 ± 0.02^a	10 ± 15.6^a	10.14 ± 0.13^a	0.28 ± 0.0^a
T2	4.6 ± 0.2	2.13 ± 0.61^a	0.240 ± 0.00^b	9 ± 4.47^b	19.84 ± 0.42^b	0.48 ± 0.0^b
T3	4.1 ± 0.4	1.41 ± 0.26^a	0.312 ± 0.04^c	5 ± 7.68^c	11.99 ± 0.32^a	0.31 ± 0.0^a
p-value	0.183	0.000	0.001	0.001	0.000	0.000

Means in the same column followed by different superscript letters are significantly different (p ≤ 0.05). SOC: Soil Organic Carbon.

Table 5: Economic analysis of different fertilization treatments for rainfed rice production (FCFA ha^{-1}).

Treatment	Avg. Yield (kg ha^{-1})	Gross Product	Total Input Cost	Gross Value Added
T0	3,600	3,600,000	637,500	562,500
T1	3,990	3,990,000	737,500	650,500
T2	5,059	5,059,000	907,500	1,310,500
T3	4,390	4,390,000	807,500	655,833

Table 6: Pearson correlation coefficients among measured growth and yield parameters of rainfed rice across all fertilization treatments (n = 12). Values are correlation coefficients with significance at *p < 0.05. Plant height and tillers measured at 75 DAS; yield components and grain yield determined at physiological maturity.

Parameter	Plant height	Tillers per plant	Panicles per m²	Grains per panicle	Filled grains (%)	1000-grain weight	Grain yield
Plant height	1.000	0.038	0.302	-0.220	0.079	0.210	0.331
Tillers per plant	0.038	1.000	-0.097	-0.190	-0.339	-0.120	-0.272
Panicles per m²	0.302	-0.097	1.000	-0.310	0.554*	0.410	0.557*
Grains per panicle	-0.220	-0.190	-0.310	1.000	0.574*	0.450	0.557*
Filled grains (%)	0.079	-0.339	0.554*	0.574*	1.000	0.520	0.388
1000-grain weight	0.210	-0.120	0.410	0.450	0.520	1.000	0.574*
Grain yield (t ha^{-1})	0.331	-0.272	0.557*	0.557*	0.388	0.574*	1.000

the highest total input cost (907,500 FCFA ha^{-1}), primarily due to pigeon pea biomass acquisition, it generated the highest gross product (5,059,000 FCFA ha^{-1}). The gross value added (GVA) was consequently highest for T2 (1,310,500 FCFA ha^{-1}), representing a 133% increase over T0 (562,500 FCFA ha^{-1}). T3 showed intermediate economic performance with GVA of 655,833 FCFA ha^{-1}, while T1 yielded 650,500 FCFA ha^{-1}. Despite higher initial investment, the benefit-cost ratio was most favorable for T2 (5.6:1), compared to 5.4:1 for T1, 5.4:1 for T3, and 5.6:1 for T0. The superior yield returns from T2 compensated for its higher input costs, making it the most economically viable option.

Correlation Analysis

Pearson correlation analysis revealed significant relationships among measured parameters (Table 6). Grain yield showed strong positive correlations with panicles per m² ($r = 0.557$, $p < 0.05$), grains per panicle ($r = 0.557$, $p < 0.05$), and 1000-grain weight ($r = 0.574$, $p < 0.05$). Plant height was moderately correlated with yield ($r = 0.331$), while tiller number showed a weak negative correlation ($r = -0.272$), suggesting potential competition among excessive tillers for resources. The percentage of filled grains correlated positively with yield ($r = 0.388$) and strongly with grains per panicle ($r = 0.574$, $p < 0.05$), indicating the importance of both grain number and grain filling efficiency for final yield. Among yield components, panicle density showed positive correlation with filled grains percentage ($r = 0.554$, $p < 0.05$), while a negative correlation was observed between panicles per m² and grains per panicle ($r = -0.310$), suggesting a trade-off between these two components.

Discussion

Soil Fertility Enhancement Through Integrated Nutrient Management

The initial soil at Nkolbisson was acidic (pH 4.4) and low in available potassium, consistent with the highly weathered, nutrient-depleted Oxisols common in humid tropical regions of Central Africa [40]. The significant improvement in soil available phosphorus (P) and exchangeable potassium (K) under the integrated pigeon pea + NPK treatment (T2) aligns with the established role of leguminous residues in enhancing nutrient cycling and soil fertility [6]. Pigeon pea is particularly effective at mobilizing sparingly soluble soil P through root exudation of organic acids (e.g., piscidic acid) that chelate Fe and Al, thereby releasing occluded P [20, 23]. Our findings support recent work by [22], who reported a 35–40% increase in plant-available P in maize systems amended with pigeon pea residues in western Kenya.

The marked increase in soil total nitrogen under T3 (NPK + urea) was expected due to the high N-input from urea. However, the more favorable C/N ratio under T2 (9:1) suggests a more balanced nutrient mineralization-immobilization dynamic, promoting sustained N release and reducing leaching losses—a critical advantage in rainfed systems prone to nutrient loss [3]. This is consistent with the findings of [30], who demonstrated that legume-integrated systems maintain higher N-use efficiency compared to sole mineral fertilization in sub-Saharan Africa.

Plant Growth and Physiological Responses

The superior plant height and tiller production under T2 can be attributed to the synergistic effects of improved soil physical structure, enhanced nutrient availability, and possibly rhizosphere stimulation by organic amendments [15]. The gradual decomposition of pigeon pea biomass likely provided a steady supply of N and other nutrients throughout the growing season, matching the demand curve of rice—particularly during critical growth stages such as tillering and panicle initiation [34]. In contrast, the sole NPK (T1) and split-urea (T3) treatments may have induced more rapid, but less synchronized, nutrient release, leading to higher early vigor but less sustained growth.

The leaf color index (LCC) results further support this; T2 maintained darker green leaves (LCC 5–6) later into the reproductive phase, indicating better N retention and availability. This aligns with findings by [10], who reported that integrated organic–mineral fertilization in Bangladesh improved the nitrogen nutrition index (NNI) of rice and delayed leaf senescence compared to urea-only plots.

Yield Components and Grain Yield

The significant increases in panicles m^{-2}, grains per panicle, and 1000-grain weight under T2 collectively drove the 40.5% yield advantage over sole NPK. These results are consistent with the principle that yield components in cereals are strongly influenced by nutrient availability during specific phenological windows: panicle number is determined during tillering, grains per panicle during panicle initiation, and grain weight during grain filling [16]. The organic amendment in T2 likely buffered soil moisture and nutrient supply during these critical periods, reducing abiotic stress—a known benefit of residue retention in rainfed systems [11].

Our yield of 5.06 t ha^{-1} under T2 exceeds the average rainfed rice yield in Cameroon (~2.5 t ha^{-1}; [7]) and approaches the genetic potential of NERICA 8 under favorable management (6–7 t ha^{-1}; [27]). This suggests that nutrient limitations, rather than varietal potential, are a primary constraint to productivity in the region. Similar yield benefits from pigeon pea integration have been reported in Malawi and Tanzania, where legume–cereal rotations increased rice yields by 30–50% [18].

Soil Health and Nutrient Cycling Implications

The post-harvest soil analysis reveals important nutrient cycling dynamics. The significant increase in available P under T2 (+4.55 mg kg^{-1}) not only reflects P mobilization by pigeon pea but also suggests reduced P fixation due to organic acid-induced changes in soil chemistry [8]. This is ecologically significant given that P fixation is a major constraint in acidic tropical soils [14].

The maintenance of soil organic carbon (SOC) under T2, compared to declines under T1 and T3, underscores the role of organic inputs in mitigating SOC depletion—a widespread challenge in continuous cereal systems [42]. Although SOC levels remained below the initial status across all treatments (likely due to rapid mineralization in the humid tropics), the slower decline under T2 suggests that integrated management can decouple crop production from soil degradation—a key objective of sustainable intensification [37].

Economic Viability and Adoption Potential

The economic analysis demonstrates that despite higher initial costs, the integrated pigeon pea system (T2) generated the highest gross value added (GVA), primarily due to substantial yield gains. This aligns with recent evidence from West Africa showing that although legume-based systems require more labor for residue management, they offer better risk-adjusted returns than pure mineral fertilization [33]. The lower and more variable GVA under T3 (NPK + urea) highlights the economic vulnerability associated with reliance on purchased N fertilizers, particularly given price volatility and access issues in rural Cameroon [17].

For smallholder farmers, the use of locally available pigeon pea residues offers a strategic pathway to reduce dependence on external inputs while building soil capital—a principle central to agroecological transitions [39]. However, adoption may be constrained by biomass availability, labor for collection and incorporation, and knowledge gaps—barriers that have been documented in similar contexts [12].

Limitations and Research Gaps

This study was conducted over a single season at one location, which limits extrapolation of results across temporal and spatial scales. Inter-annual rainfall variability and longer-term soil changes (e.g., SOC accumulation, pH adjustment) require multi-year assessment [32]. Furthermore, the nutrient contribution from pigeon pea was estimated via biomass analysis; isotopic tracing (e.g., ^{15}N) could provide more precise quantification of N transfer and utilization efficiency (Chikowo et al., 2022).

Future research should also evaluate the system's resilience under climate variability, its greenhouse gas implications (particularly N_2O emissions), and the potential for scaling through farmer-participatory approaches [26].

Conclusion

Our findings demonstrate that integrating pigeon pea residues with reduced mineral NPK significantly enhances rainfed rice productivity, improves key soil fertility parameters (particularly P and K availability), and offers superior economic returns compared to conventional mineral-only fertilization. This integrated nutrient management approach aligns with the principles of ecological intensification and provides a practical, scalable option for enhancing the sustainability of rainfed rice systems in humid tropical Africa. Policymakers and extension services should prioritize strategies that facilitate biomass recycling, strengthen soil health, and reduce farmer dependency on costly mineral fertilizers.

Conclusion

This study demonstrates that the integrated use of pigeon pea (*Cajanus cajan*) biomass and reduced-rate mineral NPK fertilizer is an effective strategy for enhancing the productivity and sustainability of rainfed rice systems in the humid forest zone of Central Cameroon. The incorporation of pigeon pea residues (17 t ha^{-1}) with NPK (200 kg ha^{-1}) resulted in significantly superior rice growth, higher yield components (panicles m^{-2}, grains per panicle, 1000-grain weight), and a grain yield increase of 40.5% compared to NPK alone. Beyond crop performance, this integrated approach improved key soil fertility indicators, notably increasing available phosphorus and exchangeable potassium while maintaining a more favorable soil C/N ratio conducive to sustained nitrogen mineralization.

Economically, despite higher initial input costs, the pigeon pea-NPK combination generated the highest gross value added, confirming its viability as a profitable nutrient management option for smallholder farmers. These findings strongly support the hypothesis that legume-based organic amendments can partially replace mineral fertilizers while enhancing system resilience and soil health.

We therefore recommend the promotion of integrated pigeon pea biomass (17 t ha^{-1}) with 200 kg ha^{-1} NPK (20-10-10) as a best-bet practice for rainfed rice production in similar agro-ecological zones. To facilitate adoption, extension programs should emphasize:

1. On-farm production or local sourcing of pigeon pea biomass,

2. Practical training on residue incorporation and compost management,

3. Complementary soil acidity management (e.g., liming) where necessary, and

4. Access to affordable, quality NPK fertilizer to ensure balanced nutrition.

Future research should investigate long-term effects on soil carbon sequestration, greenhouse gas balances, and system productivity under variable climate conditions, as well as explore efficient scaling pathways through farmer participatory trials and value-chain development for pigeon pea.

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Conflict of Interest

The authors declare no conflicts of interest.

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