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Sustainable Intensification of Rainfed Rice through Pigeon Pea Biomass and Mineral Fertilizer Integration under Contrasting Cropping Conditions in Nkolbisson, Cameroon

Georges Simplice Kameni Kouedeu[1*], Bertrand Kenzong[1], Désiré Evariste Moundjeu[1], Hortense Mafouasson[2], Diane Liliane Djatsa[1], Elza Chirelle Segnou Mbougna[1], Hassan Yap Mfouapon[1], Geordan Fabrice Meutsebo[1], Primus Tamfuh Azinwi[1,3], Emile Temgoua[1]

[1]Department of Soil Sciences, Faculty of Agronomy and Agricultural Sciences, University of Dschang, Dschang, Cameroun
[2]Institute of Agricultural Research for Development, Yaounde, Cameroon
[3]Department of Mining and Mineral Engineering, National Higher Polytechnic Institute, University of Bamenda, Bambili, Cameroon
Email: *kouedeu2008@yahoo.fr

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Abstract

Soil fertility depletion remains a major challenge in upland rice systems across sub-Saharan Africa, where resource-poor farmers often lack access to mineral fertilizers. This study evaluated the agronomic and economic performance of integrated nutrient management in upland rice, using pigeon pea (*Cajanus cajan*) biomass combined with mineral fertilizer (NPK: 20-10-10). Four treatments were compared: T0 (control, no input), T1 (biomass only), T2 (biomass + mineral fertilizer), and T3 (mineral fertilizer only). Results showed that T2 (biomass + NPK) produced the tallest plants (≈104 cm at 60 - 75 DAS), the highest tiller density, and the greatest grain yield (4700 $kg \cdot ha^{-1}$), outperforming T3 (3240 $kg \cdot ha^{-1}$), T1 (2700 $kg \cdot ha^{-1}$), and T0 (1950 $kg \cdot ha^{-1}$). In terms of economic returns, T2 achieved the highest gross value added (GVA, 232,800 $XAF \cdot ha^{-1}$; where GVA = gross output minus intermediate costs), net return (157,800 $XAF \cdot ha^{-1}$), and benefit-cost ratio (BCR = 2.2). Interestingly, T1 (biomass only) yielded the highest BCR (2.4), reflecting its low input costs despite moderate yield. These findings highlight that integrating pigeon pea biomass with mineral fertilizer substantially improves rice yield and profitability, while biomass alone provides a cost-effective option for resource-constrained farmers. Integrated nutrient management therefore offers a viable pathway to sustainable intensification of upland rice production in sub-Saharan Africa.

Keywords

Upland Rice, *Cajanus cajan* Biomass, Integrated Nutrient Management, Gross Value Added, Benefit-Cost Ratio, Sustainable Intensification, Cameroon

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's most important staple crops, providing a substantial share of daily caloric intake for billions of people. In Sub-Saharan Africa, rice consumption has steadily increased over the past two decades, driven by rapid population growth, urbanization, and dietary preferences (Muthayya et al., 2014; Seck et al., 2012). However, despite this rising demand, local rice production remains insufficient, creating a persistent dependence on imports. This reliance not only depletes foreign exchange reserves but also undermines food sovereignty and poses risks to economic stability (Demont, 2015; van Oort & Zwart, 2018).

In tropical Africa, upland rice production is severely constrained by poor soil fertility. Soils are often acidic, nutrient-deficient, and degraded due to continuous cultivation without sufficient soil replenishment (Saito et al., 2013). Rainfed upland rice, which accounts for nearly 40% of the continent's rice area, is particularly vulnerable to soil degradation and erratic rainfall (Haefele et al., 2013). These challenges are computed by the high cost of mineral fertilizers, limiting their use among smallholder farmers (Masso et al., 2017). Where applied, overreliance on chemical fertilizers has sometimes resulted in negative consequences such as nutrient imbalances, soil acidification, and the depletion of organic matter (Vanlauwe et al., 2010; Liu et al., 2010).

To overcome these constraints, the Integrated Soil Fertility Management (ISFM) has a promising strategy to yield while maintaining soil health sustainably. ISFM promotes the combined use of mineral fertilizers with organic inputs to enhance nutrient availability, improve soil structure, and increase water retention (Vanlauwe et al., 2010). Among potential organic resources, pigeon pea (*Cajanus cajan*) has gained particular attention due to its multifunctional agronomic benefits. It fixes atmospheric nitrogen, develops a deep root system that mobilizes otherwise inaccessible nutrients, and produces nutrient-rich biomass (Snapp et al., 2010; Adu-Gyamfi et al., 2007). The incorporation of pigeon pea biomass into the soil has been shown to improve soil organic carbon, enhance nutrient cycling, and contribute to long-term fertility (Chikowo et al., 2004).

Despite these promising attributes, there remains limited evidence, particularly in Central Africa, on how pigeon pea biomass interacts with mineral fertilizers under contrasting cropping conditions. Generating this knowledge is critical for developing context-specific, sustainable management strategies that allow farmers to increase yields while preserving soil quality. Therefore, this study investigates the growth and yield response of rainfed upland rice to pigeon pea biomass and mineral fertilizers under different cropping conditions in Nkolbisson, Cameroon. The findings will provide valuable insights into optimizing soil fertility management in rainfed rice systems in Central Africa.

2. Materials and Methods

2.1. Study Site Description

The field experiment was conducted in Nkolbisson, approximately 15 km from Yaounde, the capital city of Cameroon (3˚51'N, 11˚30'E). The area characterized by a humid equatorial climate characterized by two rainy seasons (March-June and September-November) and two dry seasons. Annual rainfall exceeds 1500 mm, with mean temperatures ranging between 22˚C and 28˚C and relative humidity varying from 70% and 90%, creating favourable conditions for rice cultivation (Tchindjang et al., 2015).

The experimental site is located on a Ferralsol (red-yellow, according to the World Reference Base for Soil Resources; IUSS Working Group WRB (2022)), with a silt-clay loam texture. Preliminary soil analysis indicated strongly acidic conditions (pH 4.5 - 5.2), low organic matter content (1.2%), and limited concentrations of essential macronutrients such as nitrogen (N) and phosphorus (P). These properties are typical of highlighting the inherent fertility constraints faced by rainfed rice production in the region (Folefack et al., 2020).

2.2. Planting Material

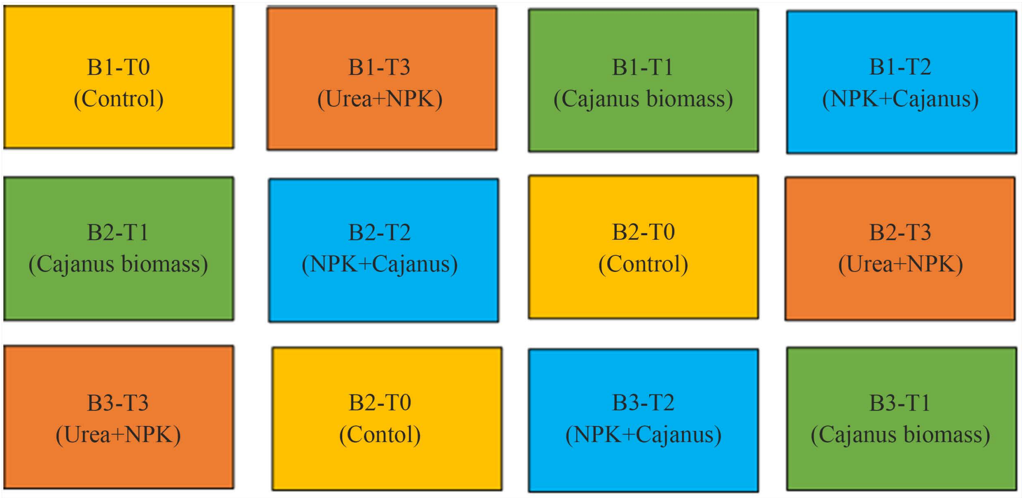
The rice variety used in this study was an improved upland cultivar (NERICA 8), selected for its adaptation to tropical agroecological conditions (Somado et al., 2008). Seeds were provided by the Institute of Agricultural Research for Development (IRAD), Yaounde. Prior to sowing, seeds were treated with a systemic fungicide (Thiram) to minimize the risk of seed-borne fungal pathogens and promote uniform germination.

2.3. Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with four treatments and three replications, giving a total of 12 experimental plots (**Figure 1**). Each plot measured 4 m^2 (2 m × 2 m), with 0.5 m spacing between plots and 1 m spacing between blocks to reduce border effects (Gomez & Gomez, 1984).

The following fertilization treatments were applied, as illustrated in **Table 1**.

The pigeon pea biomass was obtained from mature plants grown on-station for a full season. The above-ground biomass (stems and leaves) was harvested, chopped into pieces of approximately 15 - 20 cm, and air-dried to a constant weight. The application rate of 17 $t \cdot ha^{-1}$ is expressed on a dry matter basis. This relatively high rate was selected based on previous research in similar agroecologies to evaluate the upper limit of organic input response and to ensure a detectable short-term fertility effect, while acknowledging the need for future research on lower, more farmer-feasible rates (Snapp et al., 2010; Chikowo et al., 2004). The pigeon pea biomass was incorporated into the soil two weeks before sowing to allow partial decomposition and nutrient release (Shoko et al., 2019). Fertilizer application followed local agronomic recommendations (MINADER, 2015).



B1-T0 (Control)	B1-T3 (Urea+NPK)	B1-T1 (Cajanus biomass)	B1-T2 (NPK+Cajanus)
B2-T1 (Cajanus biomass)	B2-T2 (NPK+Cajanus)	B2-T0 (Control)	B2-T3 (Urea+NPK)
B3-T3 (Urea+NPK)	B2-T0 (Contol)	B3-T2 (NPK+Cajanus)	B3-T1 (Cajanus biomass)

Figure 1. Experimental design.

Table 1. Treatments.

Treatment	Fertilization Type	Applied Rate	Nature of Inputs
T0	None (Control)	0 kg·ha^{-1}	No Input
T1	*Cajanus cajan* Biomass	17 t·ha^{-1} (dry matter)	Pigeon Pea (*Cajanus cajan)* Biomass
T2	Combined Fertilization (Organic + Mineral)	200 kg·ha^{-1} NPK + 17 t/ha dry biomass	NPK + *Cajanus cajan* Biomass
T3	Enhanced Mineral Fertilization	200 kg·ha^{-1} NPK + 100 kg·ha^{-1} urea	NPK + Urea (Nitrogen Source)

2.4. Data Collection

2.4.1. Soils Analyses

Composite soil samples (0 - 30 cm depth) were collected from each plot prior to treatment application. Samples were air-dried, gently crushed, and sieved through a 2 mm mesh prior to analysis (Okalebo et al., 2002). Soil pH was measured by electrometry in a soil-to-water ratio of 1:2.5 (Thomas, 1996). Organic carbon content was determined using the Walkley and Black wet oxidation method (Nelson & Sommers, 1996). Total nitrogen was determined by the Kjeldahl digestion and distillation method (Bremner & Mulvaney, 1982). Particle size distribution was determined using the Robinson-Köhn pipette method (Gee & Or, 2002).

2.4.2. Growth Parameters

Plant height (cm) and number of tillers per plant were recorded at 15, 30, 45, 60, and 90 days after sowing (DAS), using a graduated ruler and manual counting, respectively. In each plot, five plants were randomly selected for measurement (Lafitte et al., 2002).

2.4.3. Grain Yield

Grain yield was assessed at harvest maturity. Panicles were harvested from a 1 m^2 quadrat at the centre of each plot, sun-dried to a constant moisture content (≈14%), threshed, and the grain was weighed. The values were extrapolated to yield per hectare ($kg \cdot ha^{-1}$). The number of panicles per m^2, 1000-grain weight (g), and harvest index were also determined (Fageria, 2014).

2.5. Economic Profitability Analysis

An economic assessment was carried out using a partial budget analysis, following the framework outlined by CIMMYT (1988) and adapted for local conditions. All monetary values were calculated in the local currency, the Central African CFA franc (XAF). FCFA and XAF refer to the same currency unit and have been standardized to XAF. The analysis was conducted per hectare for one cropping season and considered only costs and returns that varied between the experimental treatments.

The gross product value (GPV) for each treatment was calculated as: GPV ($XAF \cdot ha^{-1}$) = Grain Yield ($kg \cdot ha^{-1}$) × Market Price of Rice ($XAF \cdot kg^{-1}$). The market price for unmilled paddy rice was set at 250 $XAF \cdot kg^{-1}$, based on the average farm-gate price in the region during the harvest period (MINADER, 2023).

The total variable costs (TVC) included the cost of mineral fertilizers (NPK and Urea), the imputed cost of collecting and applying pigeon pea biomass (labor), and the cost of applying mineral fertilizers. Input unit costs were: NPK (20-10-10) = 450 $XAF \cdot kg^{-1}$; Urea = 500 $XAF \cdot kg^{-1}$. Labor for biomass handling and application was valued at 2500 $XAF \cdot person^{-1} \cdot day^{-1}$, based on the prevailing agricultural wage rate. The labor requirement for biomass application was recorded during the experiment.

Gross value added (GVA), representing the value created from the production process, was calculated as: GVA ($XAF \cdot ha^{-1}$) = GPV − TVC.

Two key profitability indicators were derived:

1) Net Return (NR) (This is numerically equal to GVA but represents profit):

$$NR\ (XAF \cdot ha^{-1}) = GPV - TVC$$

2) Benefit-Cost Ratio (BCR):

$$BCR = GPV/TVC$$

2.6. Statistical Analysis

All collected data were analyzed using R software (version 4.3.1; R Core Team, 2023). One-way analysis of variance (ANOVA) was conducted to evaluate treatment effects on growth, yield, and soil parameters. When significant differences were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was used for post hoc multiple comparisons (Steel et al., 1997). Assumptions of normality and homogeneity of variance were verified using the Shapiro-Wilk and Levene's tests, respectively (Shapiro & Wilk, 1965; Levene, 1960). Data were presented as means ± standard error.

3. Results

3.1. Initial Soil Properties Across Experimental Blocks

The physicochemical characteristics of soils sampled from the three blocks (B1, B2, B3) at a depth of 0 - 30 cm prior to cultivation are summarized in Table 2.

Table 2. Initial soil properties (0 - 30 cm depth) of the three experimental blocks.

Parameter	B1	B2	B3	Mean
Soil Reaction				
pH-H_2O	4.6	4.2	4.3	4.4
pH-KCl	3.8	3.7	3.7	3.7
ΔpH	−0.8	−0.5	−0.6	−0.7
ORGANIC MATTER				
Organic C (%)	3.56	3.90	2.19	3.23
OM (%)	6.13	6.72	4.77	5.57
Total N (g/kg)	1.63	1.85	1.21	1.56
C/N Ratio	22	21	17	20
Exchangeable Cations (cmol(+)·kg^{-1})				
Ca	1.84	2.56	3.01	2.47
Mg	0.88	1.36	2.24	1.49
K	0.35	0.51	0.20	0.35
Na	0.06	0.24	0.24	0.18
Sum of Bases (S)	3.13	4.67	5.69	4.50
CEC (pH 7)	14.17	17.14	20.00	17.10
Base Saturation (%)	22	27	28	26
Available P (Bray II, mg/kg)	15.69	14.36	15.82	15.29
EC (mS/cm)	0.06	0.09	0.08	0.08
Particle Size Distribution (%)				
Sand	37.0	40.5	39.0	38.83
Silt	26.0	13.5	20.5	20.00
Clay	37.0	46.0	40.5	41.17

The soil reaction, measured both in water (pH-H_2O) and in potassium chloride solution (pH-KCl), revelated that soils across the blocks were strongly acidic. The pH-H_2O values ranged from 4.2 to 4.6 (mean 4.4), while pH-KCl values were slightly lower (3.7 - 3.8). The negative ΔpH (~−0.7) confirmed the presence of active acidity, which may reduce nutrient availability and microbial activity. Organic carbon content ranged from 2.19% (B3) to 3.90% (B2), with a mean of 3.23%, corresponding to 4.77% - 6.72% organic matter. These values indicate moderate to relatively high organic matter levels, contributing positively to soil structure cycling Total nitrogen varied between 1.21 g/ and 1.85 g·kg^{-1} (mean 1.56 g·kg^{-1}), while the C/N ratio (17 - 22, mean 20) suggested a balanced decomposition and nitrogen mineralization potential.

Exchangeable bases showed moderate variability: calcium (Ca^{2+}) ranged from 1.84 to 3.01 cmol(+)·kg^{-1}, magnesium (Mg^{2+}) from 0.88 to 2.24 cmol(+)·kg^{-1}, while potassium (K^{+}) and sodium (Na^{+}) remained comparatively low, averaging 0.35 and 0.18 cmol(+)·kg^{-1}, respectively. The sum of exchangeable bases (S) averaged 4.50 cmol(+)·kg^{-1}. Cation exchange capacity (CEC, pH 7) was relatively high (14.17 - 20.00 cmol(+)·kg^{-1}), but base saturation was low (22% - 28%; mean = 26%), consistent with the strongly acidic nature of these soils.

Available phosphorus (Bray II) was limited (14.36 - 15.82 mg·kg^{-1}), indicating potential phosphorus deficiency for crop growth. Electrical conductivity (EC) remained low (0.06 - 0.09 mS·cm^{-1}), confirming the absence of salinity constraints. Soil texture was balanced, ranging from loam to clay loam, with sand (37.0% - 40.5%), silt (13.5% - 26.0%), and clay (37.0% - 46.0%). Overall, the soils were characterized by strong acidity, moderate organic matter and nitrogen content, relatively high CEC, but low base saturation and phosphorus availability. These fertility limitations highlight the importance of soil amendments, particularly organic inputs such as pigeon pea biomass and complementary mineral fertilizers, to optimize nutrient availability and enhance rice productivity.

3.2. Chemical Characteristics of the Biomass

The chemical composition (Table 3) of the pigeon pea (*Cajanus cajan*) biomass used in this study underscores its potential as a nutrient source for soil amendment and crop production. Total nitrogen (N) content was 25.10 g·kg^{-1} (2.51%), reflecting a moderate to high nitrogen level enhancing microbial activity and improving soil N availability, particularly in nitrogen-deficient environments.

The biomass is also rich in essential macronutrients. Potassium (K) concentration was the highest among analysed cations, at 5235.78 mg·kg^{-1}, highlighting its potential to improve potassium supply for plant water regulation and enzyme activation. Calcium (Ca) and magnesium (Mg) were present at 4240.0 mg·kg^{-1} and 2721.60 mg·kg^{-1}, respectively, contributing to structure, root development, and nutrient uptake efficiency.

Phosphorus (P) content of 968.16 mg·kg^{-1} suggests that the biomass can supply a critical nutrient for early root growth and energy transfer in plants. Sodium (Na), present at 134.79 mg·kg^{-1}, is minor but should be monitored in salinity-sensitive environments.

Overall, the pigeon pea biomass is chemically rich, particularly in nitrogen, potassium, and calcium, making it a highly valuable organic amendment. Its balanced nutrient composition supports its use in sustainable agriculture, especially in systems where mineral fertilizers are limited or costly.

Table 3. Chemical characteristics of the applied pigeon pea biomass (dry matter basis).

Parameter	Value
Nitrogen (N)	2.51%
Phosphorus (P)	968.16 mg·kg^{-1}
Potassium (K)	5235.78 mg·kg^{-1}
Calcium (Ca)	4240.0 mg·kg^{-1}
Magnesium (Mg)	2721.60 mg·kg^{-1}
Sodium (Na)	134.79 mg·kg^{-1}

3.3. Effects of Fertilization Treatments on Plant Height at Different Growth Stages

Table 4 and Figure 2 present the effect of fertilization treatments on Plant height at different growth stages. Plant height increased progressively across all treatments as the crop developed from 30 to 75 days after sowing (DAS), with marked differences between treatments at each growth stage.

Table 4. Effect of fertilization treatments on plant height (cm) at different stages.

Growth Stage	T0 (Control)	T1 (*C. cajan* Biomass)	T2 (*C. cajan* + 20-10-10)	T3 (20-10-10 + Urea)
30 DAS	58.88 ± 14.11^{a}	70.00 ± 9.37^{b}	71.75 ± 10.36^{b}	73.08 ± 9.68^{b}
45 DAS	60.45 ± 10.65^{a}	78.52 ± 7.37^{b}	82.78 ± 12.12^{b}	81.98 ± 10.52^{b}
60 DAS	61.85 ± 20.43^{a}	90.80 ± 23.17^{b}	**104.43 ± 12.75^{c}**	93.78 ± 7.66^{b}
75 DAS	70.75 ± 16.55^{a}	96.45 ± 14.27^{b}	**104.53 ± 12.78^{c}**	94.50 ± 7.09^{b}

Means followed by the same letter within a row are not significantly different at $p < 0.05$.

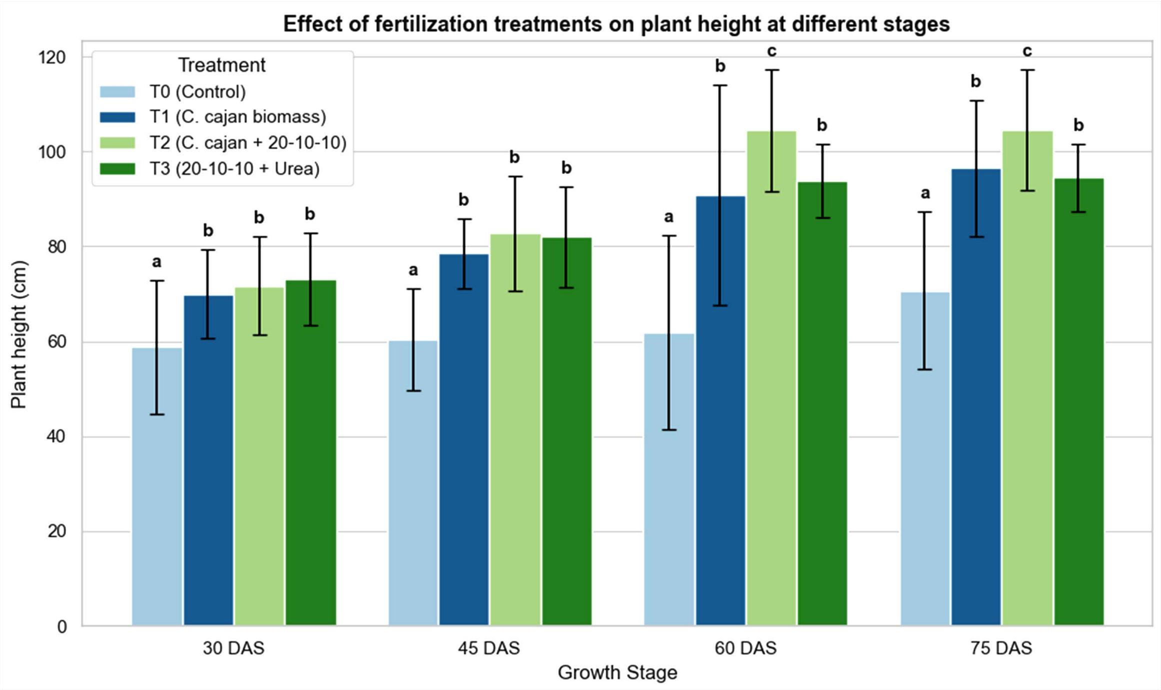


Figure 2. Effect of fertilizer treatment on plant height at different growth stages.

At 30 DAS, plants in the control treatment (T0) exhibited the lowest mean height (58.88 cm ± 14.11 cm), whereas all fertilized treatments showed significantly greater heights. Spatially, plots receiving pigeon pea (*Cajanus cajan*) biomass alone (T1) reached 70.00 cm ± 9.37 cm, while the combined mineral fertilizer and biomass treatment (T2) recorded 71.75 cm ± 10.36 cm. The NPK + urea treatment (T3) resulted in the highest mean height of 73.08 cm ± 9.68 cm. All fertilized treatments were statistically different from the control ($p < 0.05$).

By 45 DAS, these trends became more pronounced. Control plants averaged 60.45 cm ± 10.65 cm, remaining significantly shorter than those in the fertilized plots. Plants in T1 and T3 exceeded 78 cm, while T2 reached 82.78 cm ± 12.12 cm. Fertilized plots exhibited a more uniform and vigorous canopy, highlighting the positive effects of pigeon pea biomass and mineral fertilizers on vegetative growth.

At 60 DAS, growth differences among treatments became more pronounced. Plants in T2 (pigeon pea biomass + mineral fertilizer) were the tallest, with a mean height of 104.43 cm ± 12.75 cm, significantly exceeding all other treatments. Heights in T1 (pigeon pea biomass alone) and T3 (NPK + urea) ranged from 90.80 cm ± 23.17 cm to 93.78 cm ± 7.66 cm, whereas the control (T0) remained at 61.85 cm ± 20.43 cm, reflecting limited growth under unfertilized conditions. By 75 DAS, the trend persisted. T2 maintained its lead, producing the tallest plants (104.53 cm ± 12.78 cm) with a statistically significant advantage over other treatments. T1 and T3 exhibited comparable performance (96.45 cm ± 14.27 cm and 94.50 cm ± 7.09 cm, respectively), while T0 remained the shortest (70.75 cm ± 16.55 cm). Across all growth stages, T2 consistently outperformed T1 and T3, and all fertilized treatments clearly exceeded the control in height, indicating a sustained growth advantage throughout the crop cycle. These results demonstrate that the integration of pigeon pea biomass with mineral fertilizer markedly the improved growth is likely due to better nutrient availability, synergistic effects of organic and mineral inputs, and enhanced microbial activity in the soil.

3.4. Effects of Fertilization Treatments on Tiller Production

Table 5 and Figure 3 present the effect of fertilization treatments on tiller number, a critical determinant of crop productivity in cereals. The number of tillers per plant was assessed at 30, 45, 60, and 75 DAS. The significant treatment effects were observed at all growth stages ($p < 0.05$).

Table 5. Effect of fertilization treatments on tiller number per plant at different stages.

Growth Stage	T0 (Control)	T1 (*C. cajan* Biomass)	T2 (*C. cajan* + 20-10-10)	T3 (20-10-10 + Urea)
30 DAS	3.32 ± 2.75^{a}	5.28 ± 3.14^{b}	$\mathbf{6.40 \pm 2.29^{c}}$	5.70 ± 2.12^{b}
45 DAS	3.70 ± 2.30^{a}	5.93 ± 2.62^{b}	6.63 ± 2.64^{b}	6.08 ± 2.02^{b}
60 DAS	6.10 ± 2.73^{a}	6.88 ± 2.16^{bc}	$\mathbf{7.70 \pm 2.81^{bc}}$	6.88 ± 3.35^{b}
75 DAS	6.13 ± 5.57^{a}	7.45 ± 6.31^{b}	$\mathbf{8.43 \pm 3.83^{bc}}$	7.13 ± 3.29^{d}

Means followed by the same letter within a row are not significantly different at $p < 0.05$.

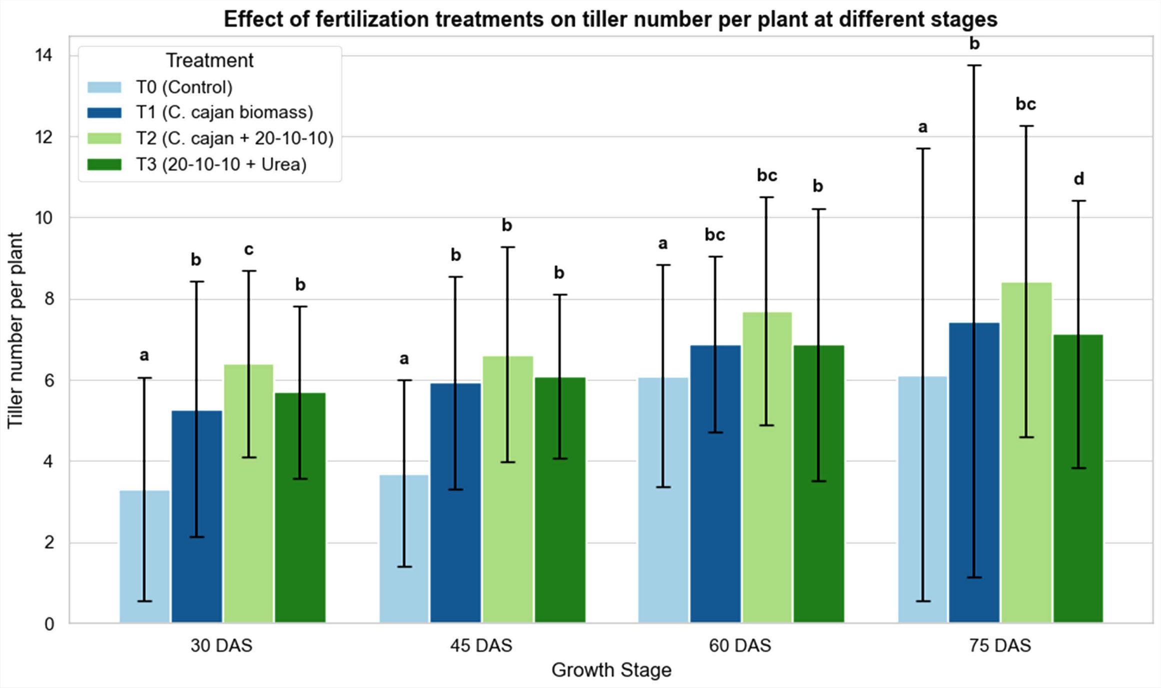


Figure 3. Effect of fertilization treatments on tiller number.

At 30 DAS, plants in the control (T0) produced the fewest tillers (3.32 ± 2.75), whereas the combined application of pigeon pea biomass and NPK (T2) resulted in the highest tiller count (6.40 ± 2.29), significantly exceeding all other treatments. Both T1 (pigeon pea biomass alone) and T3 (NPK + urea) also increased tiller numbers compared to the control, demonstrating the positive influence of organic and/or mineral nutrient inputs on vegetative development.

The trend persisted at 45 DAS, with T2 (pigeon pea biomass + NPK) maintaining the highest tiller number (6.63 ± 2.64), although differences among T1 (pigeon pea biomass alone), T2, and T3 (NPK + urea) were not statistically significant. The control (T0) remained significantly lower, highlighting the importance of fertilization for early tiller formation. At 60 DAS, tiller numbers peaked. T2 again produced the highest count (7.70 ± 2.81), followed closely by T3 and T1 (both 6.88). All fertilized treatments were significantly superior to the control, which averaged 6.10 tillers. By 75 DAS, T2 sustained the highest tiller production (8.43 ± 3.83), demonstrating the lasting effect of combined organic-mineral fertilization. T1 and T3 also maintained higher tiller numbers than the control, but were less effective than T2. The consistent superiority of T2 across all growth stages underscores the effectiveness of integrating pigeon pea biomass with mineral fertilizers for enhancing vegetative growth and potentially increasing yield components.

3.5. Effect of Treatments on the Average Number of Grains per Panicle

The number of grains per panicle is a key yield-determining trait in rice. Data in

Table 6 show that fertilization treatments had a significant effect on this parameter ($p < 0.05$).

Table 6. Effect of treatments on the average number of grains per panicle.

Treatment	Average Grain Number per Panicle
T0 (Control)	30.23 ± 2.10^a
T1 (*C.cajan* biomass)	40.22 ± 2.60^a
T2 (*C. cajan* + NPK)	**58.35 ± 13.23^b**
T3 (NPK + Urea)	47.03 ± 3.36^b

Means with different letters are significantly different at $p < 0.05$.

The highest average number of grains per panicle was observed in T2 (pigeon pea biomass + NPK), with 58.35 grains ± 13.23 grains, significantly exceeding T3 (NPK + urea, 47.03 ± 3.36) and the control (T0, 30.23 ± 2.10). T3 also outperformed T1 (pigeon pea biomass alone, 40.22 ± 2.60), whereas T1 was not significantly different from the control.

These findings highlight the agronomic value of integrating pigeon pea biomass with mineral fertilizers, as the organic amendment likely enhanced soil biological activity, nutrient cycling, and rhizosphere microclimate, thereby improving spikelet fertility and grain filling.

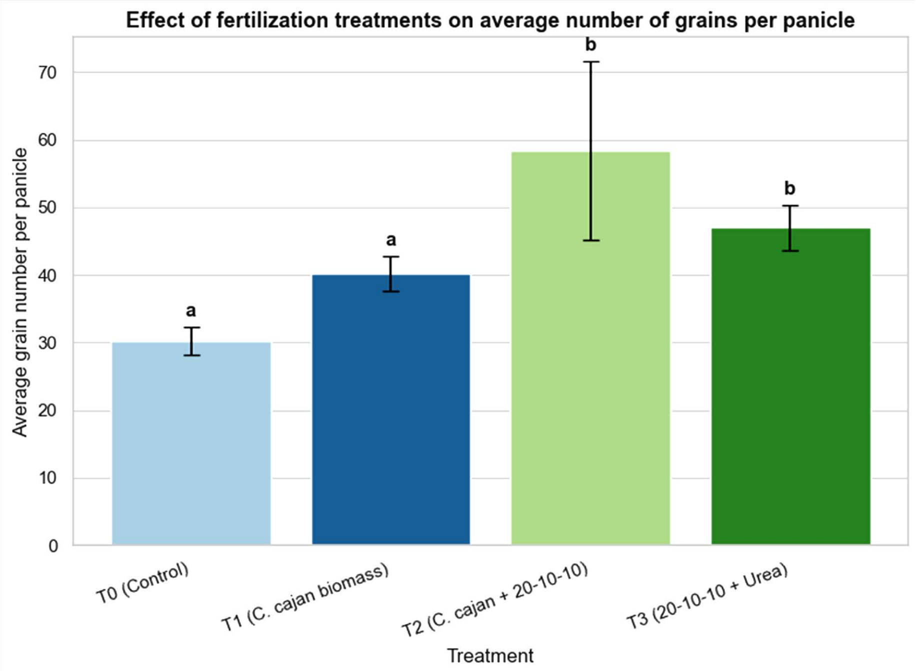


Figure 4. Effect of treatments on the average number of grains per panicle.

The bar graph (**Figure 4**) illustrating the effect of fertilization treatments on the average number of grains per panicle reveals significant differences in rice yield potential. The highest grain number per panicle was observed in T2 (pigeon pea biomass + NPK, 58.35 ± 13.23), significantly outperforming all other treatments. The mineral-only treatment (T3, NPK + urea) also showed a notable increase (47.03 ± 3.36) compared to the control (T0) and T1 (pigeon pea biomass alone, 40.22 ± 2.60). Although T1 improved over the control (30.23 ± 2.10), it did not reach the level of T2 or T3.

The larger variability observed in T2 indicates some plot-to-plot differences, but its overall superior performance highlights the synergistic effect of combining pigeon pea biomass with mineral fertilizers. These results demonstrate that integrated nutrient management, combining organic residues with mineral fertilization, can significantly enhance rice productivity and provide a sustainable strategy for improving grain yield in rainfed systems.

3.6. Economic Analysis of the Treatments

3.6.1. Economic Return of Treatments

The economic evaluation (Table 7 and Figure 5) clearly demonstrates that the integration of pigeon pea biomass with mineral fertilizer (T2) provides the most advantageous outcome in terms of profitability. All monetary values are expressed in Central African CFA francs (XAF).

Table 7. Economic returns from different fertilization treatments.

Treatment	Total Cost (XAF·ha^{-1})	Gross Revenue (XAF·ha^{-1})	Net Return (XAF·ha^{-1})	Benefit-Cost Ratio (BCR)
T0 (Control)	30.000	97.600	67.600	1.3
T1(Biomass)	40.000	135.000	95.000	2.4
T3(NPK + Urea)	65.000	162.000	97.000	1.8
T2(Biomass + NPK)	70.000	235.000	**165.000**	**2.3**

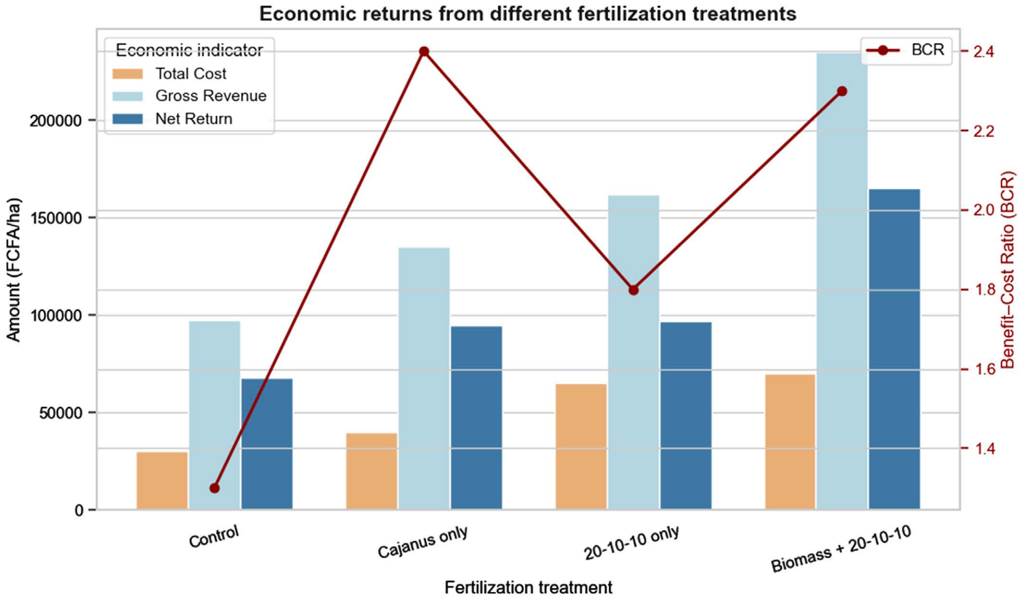


Figure 5. Economic returns from different fertilization treatments.

This combined treatment (T2) achieved the highest gross revenue (235,000 FCFA/ha) and net return (165,000 FCFA/ha), with a competitive benefit-cost ratio (BCR) of 2.3. These results indicate that the additional cost of incorporating biomass is more than compensated by the corresponding increase in yield and revenue.

In comparison, the mineral-only treatment (T3, 20-10-10 + urea) produced a relatively high gross revenue (162,000 FCFA/ha) but a lower BCR (1.8), reflecting higher input costs (65,000 FCFA/ha) without a proportional increase in returns. This highlights that yield gains from mineral fertilizer alone may not always translate into optimal economic efficiency.

The biomass-only treatment produced a net return of 95,000 FCFA/ha and the highest BCR (2.4), indicating excellent cost-effectiveness despite a lower absolute yield. This suggests that pigeon pea biomass application can serve as a viable low-input strategy for resource-constrained farmers, particularly where mineral fertilizers are expensive or supply chains are unreliable.

As expected, the control (T0, no fertilization) exhibited the weakest economic performance, with the lowest gross revenue (97,600 FCFA/ha), net return (67,600 FCFA/ha), and BCR (1.3), underscoring the economic disadvantage of relying solely on the inherent fertility of depleted soils in rainfed rice systems. Overall, these findings emphasize that integrating organic-mineral fertilization can enhance yield performance and profitability, providing short-term financial gains and potential long-term benefits for soil health. This approach aligns with principles of sustainable intensification, offering a balanced pathway to improve farmer livelihoods while maintaining ecological integrity.

3.6.2. Added Values of Treatments per Hectare

Evaluation of Gross Value Added (GVA) across treatments (T0 - T3) revealed significant inter-treatment variability in economic performance (**Figure 6**). Based on the mean GVA values presented in **Table 8**, the correct ranking is T2 > T1 > T3 > T0. Treatment T2 achieved the highest average GVA (1,310,500 currency units·ha^{-1}), substantially outperforming all other treatments. In contrast, the control (T0) exhibited the lowest profitability, with an average GVA of 562,500 currency units·ha^{-1}. The GVA for T1 (650,500 XAF·ha^{-1}) was marginally higher than that of T3 (655,000 XAF·ha^{-1}), though the difference was not statistically significant given the high variability.

High GVA for T2 was primarily driven by strong performance in blocks B1 (1,687,500) and B2 (2,240,500), while B3 recorded a marginal profit (3500), suggesting sensitivity to site-specific constraints. T1 (pigeon pea biomass alone) displayed moderate profitability (GVA of 650,500), but with high variability, including a negative GVA in B3 (−31,500), indicating vulnerability to environmental or management-related stressors. T3 (NPK + urea) yielded intermediate returns (655,833), surpassing T0 but lagging behind T1 and T2.

These results (**Table 8**) further support the economic advantage of integrating organic residues and mineral fertilizers, demonstrating that combined nutrient management can simultaneously maximize productivity and financial returns in rainfed rice systems.

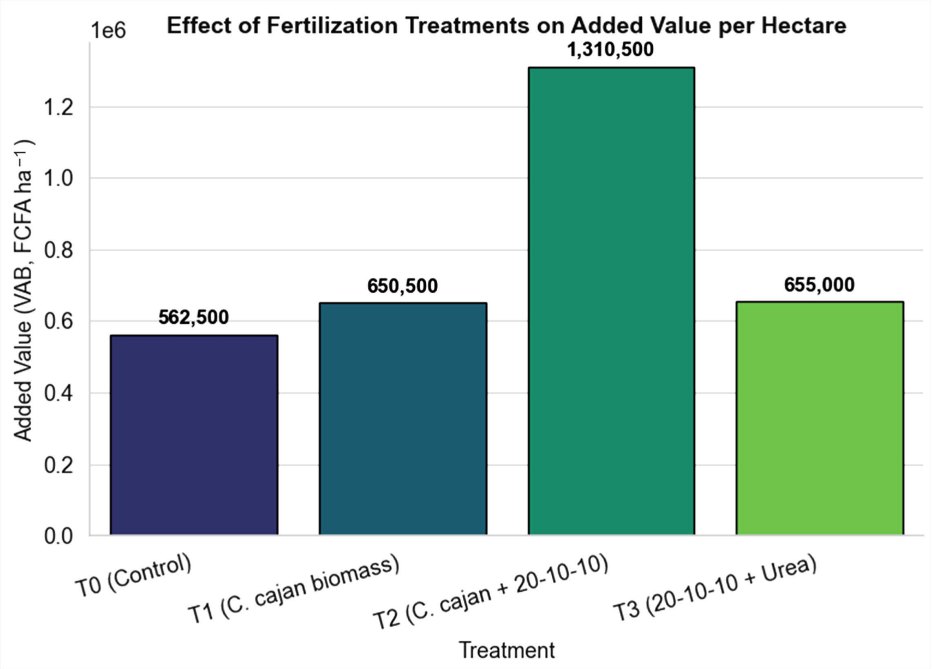


Figure 6. Average gross added values per treatment.

Table 8. Added value per hectare under different fertilization treatments.

Treatment	Gross Product (XAF·ha^{-1})	Input Cost (XAF·ha^{-1})	Added Value (XAF·ha^{-1})
T0 (Control)	1,200,000 ± 300,000	637,500 ± 0	**562,500 ± 300,000**
T1 (Biomass)	1,388,000 ± 642,000	737,500 ± 0	**650,500 ± 627,000**
T2 (Biomass + NPK)	2,218,000 ± 1,243,000	907,500 ± 0	**1,310,500 ± 1,126,000**
T3 (NPK + Urea)	1,463,000 ± 401,000	807,500 ± 0	**655,000 ± 400,000**

4. Discussion

4.1. Agronomic Effects of Integrated Nutrient Management

The present study demonstrates that the integrated application of pigeon pea biomass with mineral fertilizer (Treatment T2) significantly enhanced vegetative growth, yield components, and final grain yield of upland rice. The superior performance of T2, achieving plant heights exceeding 104 cm and the highest tiller numbers, aligns with the established principle of Integrated Soil Fertility Management (ISFM), which posits that the combined use of organic and mineral inputs creates synergistic benefits (Vanlauwe et al., 2015). The organic biomass improves the soil's physical and biological properties, fostering a better root environment, while the mineral fertilizer provides readily available nutrients to meet immediate crop demands during peak growth stages (Jat et al., 2020; Kihara et al., 2020). This synergy likely explains why T2 outperformed both the sole mineral (T3) and sole organic (T1) treatments.

Recent studies in similar contexts support these findings. For instance, research in Benin on upland rice found that combining *Mucuna pruriens* biomass with NPK fertilizer resulted in significantly greater plant height and dry matter accumulation compared to either input alone (Akonde et al., 2022). Similarly, in Nigeria, the integration of poultry manure with NPK fertilizer led to a more synchronized nutrient release, matching the rice crop's uptake pattern better than synthetic fertilizers alone (Oladele & Awodun, 2019). The observed growth enhancement in T2 can therefore be attributed to improved nutrient availability, better soil moisture retention from added organic matter, and stimulated microbial activity that facilitates nutrient cycling (Mousavi & Eskandari, 2021).

4.2. Tiller Formation and Canopy Development

Tiller production is a critical determinant of panicle density and, consequently, yield potential in cereals. The consistently higher tiller count in T2, particularly at later growth stages (75 DAS), underscores the sustained nutrient supply and favourable rhizosphere conditions provided by the integrated treatment. Organic amendments like pigeon pea biomass enhance soil aggregation and porosity, promoting root proliferation and the development of secondary tillers (Chaudhary et al., 2021). Furthermore, the gradual mineralization of nitrogen from the biomass provides a steady nutrient stream during the critical tillering phase, preventing the luxury consumption and potential lodging sometimes associated with high doses of mineral nitrogen (Ghimire et al., 2019).

The role of organic matter in moderating soil microclimate is particularly crucial in rainfed systems. Studies have shown that surface-applied or incorporated residues can reduce soil temperature fluctuations and decrease evaporation, thereby conserving soil moisture (Jat et al., 2019). This improved water availability during intermittent dry spells common in the bimodal rainfall regime of Central Africa likely contributed to the sustained tiller survival and development observed in T2, compared to the more vulnerable tillers in the control and mineral-only plots (Tounkara et al., 2020).

4.3. Yield Components and Grain Production

The grain yield advantage of T2 (approximately 73% over T1 and 45% over T3) is a direct consequence of its positive impact on key yield components: productive tillers per unit area and grains per panicle. The significant increase in grains per panicle under T2 suggests that the integrated nutrient supply was optimal during the panicle initiation and grain-filling periods. Nitrogen is paramount for spikelet formation and reducing sterility (Fageria, 2014). The combination of fast-release mineral N and slow-release organic N from decomposing pigeon pea biomass likely ensured adequate N availability throughout these sensitive reproductive stages, a benefit often missing in sole mineral fertilizer applications where N may be subject to early leaching losses (Masso et al., 2017).

These results are consistent with contemporary research across Sub-Saharan

Africa. A meta-analysis by Kihara et al. (2020) concluded that ISFM practices increased cereal yields by an average of 30% - 50% compared to sole mineral fertilizer. Specifically for rice, Ndayiragije and Ntamatungiro (2022) reported that incorporating legume residues with reduced NPK doses in Burundi yielded equivalently to or better than full recommended NPK rates, highlighting the substitution value of organic inputs. Our finding that T2 yielded 4700 $kg \cdot ha^{-1}$ aligns with the potential of improved upland rice varieties under good fertility management in the region, as reported by Saito et al. (2021), who identified soil fertility as the primary yield gap factor for rainfed upland rice in West and Central Africa.

4.4. Economic Performance and Benefit-Cost Analysis

The economic analysis provides critical insights for adoption. While Treatment T2 (integrated) required the highest initial investment (70,000 $XAF \cdot ha^{-1}$), it generated the greatest net return (165,000 $XAF \cdot ha^{-1}$), demonstrating that the yield premium justified the additional cost. This finding supports the economic rationale for ISFM, which can enhance profitability despite modestly higher input costs (Manda et al., 2020). The sole biomass treatment (T1) exhibited the highest Benefit-Cost Ratio (BCR = 2.4), underscoring its exceptional efficiency for farmers with severe capital constraints. This is a vital consideration in contexts where fertilizer access is limited by cost, supply chain issues, or credit availability (Liverpool-Tasie et al., 2017).

The use of locally sourced pigeon pea biomass represents a strategy to internalize input costs within the farming system, reducing vulnerability to volatile international fertilizer prices—a pressing concern post-2021 (Torero, 2022). Furthermore, pigeon pea cultivation itself provides other livelihood benefits (e.g., food, fodder, fuelwood), enhancing overall farm resilience (Snapp et al., 2018). Our economic results resonate with studies in Malawi and Tanzania, where legume integration significantly improved farm-level profitability and reduced the economic risk profile compared to maize monocropping with fertilizer (Smith et al., 2016; Marenya et al., 2020).

However, the high variability in Gross Value Added (GVA), particularly the low return from T2 in block B3, highlights a crucial challenge. This variability likely stems from unmeasured soil heterogeneity, micro-topographic differences affecting water distribution, or biotic stresses. It reinforces the concept that ISFM is not a one-size-fits-all recipe but a set of principles that must be adapted to local biophysical and socioeconomic conditions (Vanlauwe et al., 2015; Zingore et al., 2022). Site-specific nutrient management, informed by simple soil tests or farmer knowledge, is essential to optimize returns.

4.5. Study Limitations

While this study provides valuable insights, its limitations must be acknowledged to contextualize the findings and guide future research. First, the results are derived from a single-season trial at one location. Consequently, the year-to-year variability in climate (e.g., rainfall distribution, temperature) and the site-specific nature of soil responses may limit the direct generalizability of the results across different agroecological zones or over multiple seasons in Central Africa. Second, the experimental plot size was relatively small (4 m^2), which is standard for controlled, replicated agronomic research but may not fully capture field-scale dynamics such as pest and disease pressure, water movement, or edge effects that influence crop performance in farmers' fields. These limitations underscore that our conclusions, while promising, represent an initial proof of concept. Future multi-location, multi-year trials conducted on larger plots or through participatory on-farm research are essential to validate these findings, assess their robustness under variable conditions, and develop scalable recommendations for farmers.

4.6. Implications for Policy and Research

Given the positive agronomic and economic outcomes, integrating pigeon pea biomass into fertilizer regimes could be promoted via national soil fertility improvement programs and farmer extension services. The limitations highlighted above directly inform the following research priorities:

- Multi-location, multi-season trials to validate performance across agroecological zones.
- Long-term monitoring of soil health indicators (e.g., organic carbon, microbial activity, pH) under integrated management to quantify sustainability benefits.
- Socioeconomic modelling to capture household-level impacts under fluctuating markets and climatic conditions.
- Life cycle assessments to quantify greenhouse gas emission savings relative to mineral fertilizer-only systems.
- On-farm participatory research using larger plot sizes to evaluate the technology under real-world management conditions and assess labour requirements and acceptability.

This study reinforces the principle of Integrated Soil Fertility Management (ISFM): combining organic and inorganic nutrient sources optimizes short-term productivity and long-term sustainability (Vanlauwe et al., 2010). In rainfed upland rice systems of Cameroon, *pigeon pea* biomass serves as both a soil amendment and a strategic economic buffer, enabling farmers to enhance yields, improve profitability, and safeguard soil health.

5. Conclusion

This study investigated the growth, yield, and economic performance of rainfed upland rice in response to integrated nutrient management using pigeon pea (*Cajanus cajan*) biomass and mineral fertilizers on an acidic Ferralsol in Cameroon. The results provide clear, actionable evidence that tailored nutrient management strategies can enhance both productivity and sustainability for smallholder farmers with varying levels of resource access.

The integrated application of pigeon pea biomass with mineral NPK (T2) delivered superior agronomic and economic outcomes, producing the highest grain yield and net return. This treatment leverages the synergy between immediate nutrient availability from fertilizers and the long-term soil-building benefits of organic matter. Consequently, for farmers with reliable access to capital and mineral fertilizers, the combined organic-mineral approach (T2) is the recommended strategy to maximize productivity and profitability.

Conversely, the biomass-only treatment (T1) demonstrated exceptional economic efficiency, achieving the highest benefit-cost ratio. This finding is critically important for the large segment of resource-constrained smallholders. For farmers facing capital limitations or unreliable fertilizer supply chains, the application of pigeon pea biomass alone is a highly viable and recommended low-input strategy. It provides a substantial yield increase over unfertilized plots, improves soil health, and minimizes financial risk.

Beyond these distinct pathways, the consistent incorporation of legume biomass represents a strategic investment in long-term system resilience. It builds soil organic carbon, enhances water retention, and reduces dependence on volatile external inputs.

To translate these findings into impact, future work should refine site-specific application rates, quantify long-term soil health benefits, and develop extension materials that clearly present these dual recommendations. Policy and subsidy programs should be designed to support both pathways: facilitating access to mineral fertilizers for farmers who can use them efficiently while promoting legume cultivation and biomass use as a foundational practice for all. This differentiated approach is essential for achieving sustainable intensification across the diverse socioeconomic landscape of upland rice farming in Central Africa.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Authors' Contributions

Georges Simplice Kouedeu Kameni, the corresponding author, conceptualized and conducted the research and drafted the original manuscript. Bertrand Kenzong contributed to material preparation, data collection, analysis, and manuscript editing. Hortense Mafouasson, Désiré Evariste Moundjeu, Diane Liliane Djatsa, Elza Chirelle Segnou Mbougna, Hassan Yap Mfouapon, Geordan Fabrice Meutsebo, Primus Tamfuh Azinwi, and Emile Temgoua contributed to editing and the manuscript. All the authors read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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