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Effect of Pigeon Pea (Cajanus Cajan) Biomass on Nitrogen Nutrition and Yield of Rainfed Rice Using Leaf Color Chart

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ABSTRACT

The high cost and low use efficiency of mineral fertilizers are major constraints to rice production for smallholder farmers in Sub-Saharan Africa. This study evaluated the efficacy of *Cajanus cajan* biomass as an alternative nitrogen source for rainfed rice, using the Leaf Color Chart (LCC) as a real-time monitoring tool. A field experiment was conducted in Nkolbisson, Cameroon, during the 2025 cropping season using a randomized complete block design with four treatments and three replications: 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} *C. cajan* biomass), and T3 (200 kg ha^{-1} NPK 20-10-10 + 100 kg ha^{-1} urea). LCC readings, yield, and nitrogen use efficiency (NUE) as Partial Factor Productivity (PFP) were assessed. Results showed that T2 maintained significantly higher ($p < 0.001$) LCC scores throughout the growth cycle, indicating superior and sustained nitrogen nutrition. This translated into a 26.8% grain yield advantage for T2 (5.06 t ha^{-1}) over T1 (3.99 t ha^{-1}). Although the Partial Factor Productivity of Nitrogen (PFPN) was highest for T1 (99.8 kg grain/kg N), the integrated T2 treatment achieved the highest absolute yield, demonstrating its effectiveness for maximizing productivity. The study demonstrates that the integrated use of *C. cajan* biomass, a key ISFM practice, provides a more stable nitrogen supply and significantly improves rainfed rice productivity, offering a sustainable and efficient alternative to sole mineral fertilization.

Keywords: *Cajanus cajan*, integrated soil fertility management, leaf color chart, nitrogen use efficiency, rainfed rice, smallholder farmers, sustainable intensification.

INTRODUCTION

Rice (*Oryza sativa* L.) is a critical staple food for over half of the world's population, with its consumption in Sub-Saharan Africa (SSA) growing faster than any other major staple (Arouna et al., 2021; FAO, 2022). In Cameroon, despite increasing demand, domestic production falls short, leading to heavy reliance on imports that strain national economies and threaten food security (Mbondji & Fon, 2023). Rainfed rice systems, which dominate smallholder production in many regions, are particularly constrained by inherently low soil fertility and declining soil organic matter, exacerbated by limited access to and inefficient use of mineral fertilizers (Djagba et al., 2022; De Vos et al., 2023).

Nitrogen (N) is the most yield-limiting nutrient in rice production, directly influencing key physiological processes including tillering, panicle development, and grain filling (Sinclair and Rufty, 2012). However, the high cost and volatile prices of mineral N fertilizers place them beyond the reach of many smallholder farmers (Tittonell and Giller, 2013). Furthermore, the agronomic efficiency of applied N in SSA is often low due to significant losses via leaching, volatilization, and denitrification, leading to poor crop responses and negative environmental impacts (Chivenge et al., 2020). This underscores the urgent need for accessible, efficient, and sustainable N management strategies.

The integration of leguminous plants into cropping systems presents a viable pathway for enhancing soil N through biological nitrogen fixation (BNF). Pigeon pea (*Cajanus cajan* [L.] Millsp.), a resilient, deep-rooted legume well-adapted to marginal soils, is particularly notable for its high biomass production and substantial N content (2.0–3.5%), making it an excellent green manure resource (Kouedeu et al., 2025). Beyond N contribution, its biomass can improve soil structure, enhance water retention, and mobilize poorly available soil phosphorus, offering multiple agro-ecological benefits (Snapp et al., 2019).

Effective N management requires timely assessment of the plant's N status. The Leaf Color Chart (LCC), a simple, non-destructive, and low-cost tool developed by the International Rice Research Institute (IRRI, 1988), enables real-time estimation of leaf N status based on chlorophyll density, which is highly correlated with tissue N concentration (Sen et al., 2011; Kulkarni & Das, 2023). While the LCC is widely recommended for guiding urea top-dressing, its utility for monitoring N dynamics in systems amended with organic nutrient sources like *C. cajan* biomass remains underexplored (Mula et al., 2010).

Therefore, this study aimed to evaluate the effect of *Cajanus Cajan* biomass on nitrogen nutrition and yield of rainfed rice using the Leaf Color Chart. The specific objectives were to: (1) monitor LCC scores across growth stages under different fertilization regimes, (2) correlate LCC scores with yield parameters, and (3) identify the most effective treatment for sustainable nitrogen management. It was hypothesized that combining NPK with *C. Cajan* biomass would improve LCC scores and yield compared to mineral fertilizers alone.

MATERIALS AND METHODS

Study site

The field experiment was conducted in Nkolbisson, Yaoundé, Centre Region of Cameroon (3°51'N, 11°30'E, 726 m a.s.l.) (Figure 1). The site experiences a humid equatorial climate with two rainy seasons (March–June and September–November) and two dry seasons. Mean annual rainfall is 1500 mm, mean temperature ranges from 22–28°C, and relative humidity is 70–90%. The area is drained by by the Mfoundi River (a branch of the Nyong River) and its tributaries which together form a dendritic drainage pattern. The area is part of the surger Cameroon Plateau, made up of an extensive plain which is interrupted here and there by half-orange hills with altitudes between 600 and 800 m. The geology is a composed of granite-gneissic rocks of the Precambrian era (Nzenti et al., 1999).

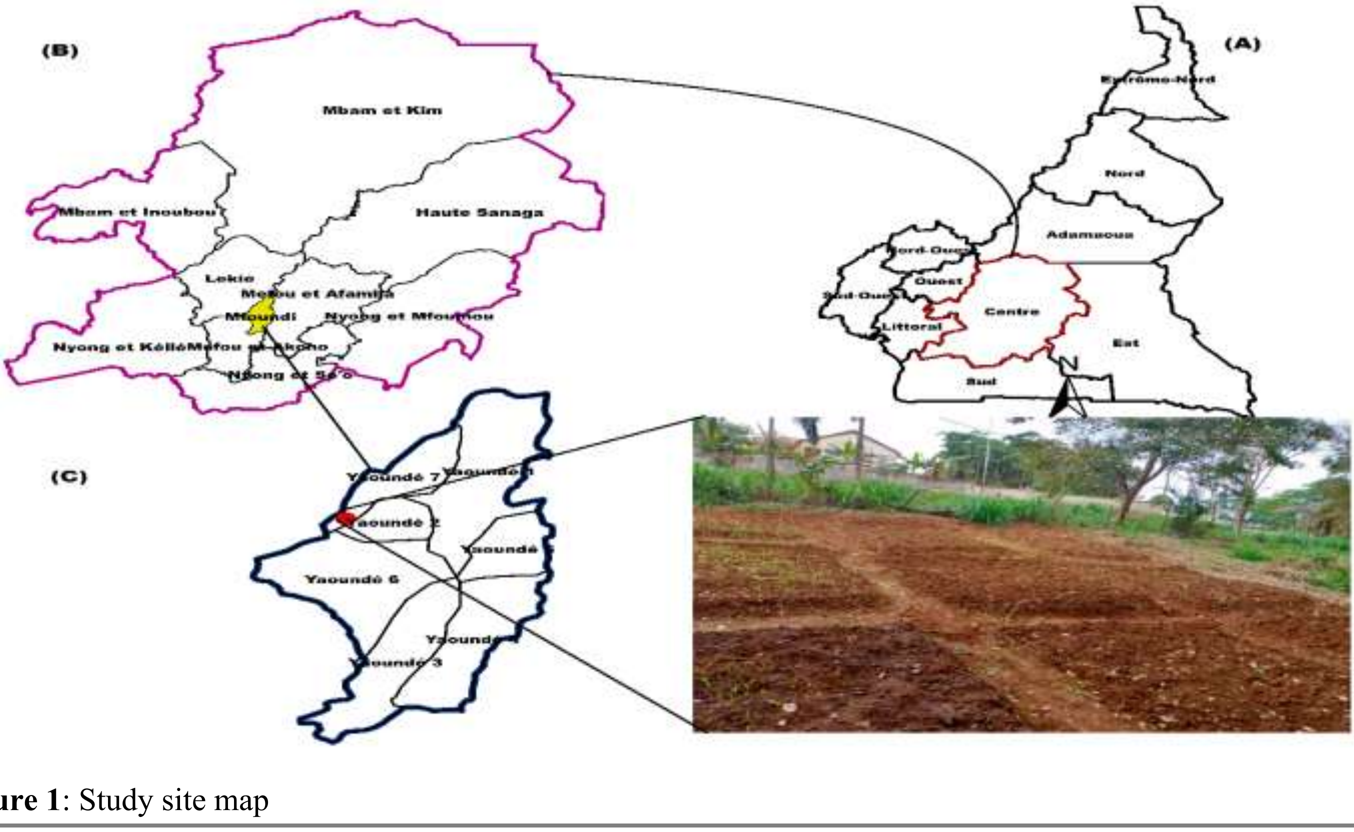

Figure 1: Study site map

Experimental design and treatments

The experiment was laid out in a randomized complete block design with three replications. The treatments consisted of:

- 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} *C. cajan* biomass
- T3: 200 kg ha^{-1}NPK (20-10-10) + 100 kg ha^{-1} urea (46% N)

Each experimental unit measured 9 m² (3 m × 3 m). The *C. cajan* biomass, consisting of dry leaves and pods collected after threshing (Figure 2A), was incorporated into the soil four days before sowing at a rate of 15.3 kg per plot (equivalent to 17 t ha^{-1}) (figure 2B). The NPK fertilizer was applied at 28 days after sowing (DAS), while urea was split-applied at panicle initiation (60-65 DAS) and flowering (70-75 DAS).

Figure 2: Preparation and application of *Cajanus cajan* biomass**: (A)** Dry biomass of *Cajanus cajan* (leaves and pods) collected after threshing. **(B)** Incorporation of *Cajanus cajan* biomass into the soil before sowing.

Crop establishment and management

NERICA 8 rice variety was used as the test crop. Seeds were sown on March 20, 2024, at a spacing of 25 cm × 25 cm with 5 seeds per hill, later thinned to 3 plants per hill at 14 days after emergence. Manual weeding was performed three times during the growing season. Other cultural practices followed recommended procedures for rainfed rice in the region.

Data collection

Leaf Color Chart measurements: LCC readings were taken at 30, 45, 60, and 75 DAS using the standard IRRI LCC with scores ranging from 1 (very light green) to 7 (very dark green). For each treatment, 60 plants were randomly selected and scored for leaf color.

Figure 3: Leaf color measurement using LCC graduated from 1 to 7

Growth and yield parameters: Plant height, number of tillers, number of panicles per m², number of grains per panicle, percentage of filled grains, 1000-grain weight, and grain yield were recorded following standard procedures.

Soil and biomass analysis: Composite soil samples (0-30 cm depth) were collected before treatment application and after harvest. The *C. Cajan* biomass was analyzed for nutrient content. Soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable bases, and cation exchange capacity were determined using standard laboratory methods.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using R software version 4.5.1. Treatment means were separated using Tukey's test at 5% probability level. Pearson correlation analysis was performed to establish relationships between LCC scores and yield parameters.

Collection and analysis of initial soil properties and C. cajan Biomass

Soil samples were air-dried and sieved (2-mm) for analysis. Soil pH was measured potentiometrically in a 1:2.5 soil-water suspension, organic carbon by the Walkley-Black method, and total nitrogen by the macro-Kjeldahl method. Available phosphorus and exchangeable potassium were extracted using Bray-1 and ammonium acetate solutions, respectively, and determined by colorimetry and flame photometry. Cation exchange capacity (CEC) and texture were analyzed via the ammonium acetate saturation and hydrometer methods, respectively. The *Cajanus cajan* biomass was analyzed for total nitrogen (Kjeldahl method) and for P, K, Ca, and Mg using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) after dry ashing.

Results

Characteristics of *Cajanus cajan* Biomass and Initial Soil Fertility

The chemical analysis confirmed the high fertilizing value of the *Cajanus cajan* biomass, particularly its rich nitrogen content of 2.51% (Table 1). The initial soil at the experimental site was strongly acidic (pH 4.4) with a moderate level of organic matter (5.57%) but low in available phosphorus (15.29 mg kg^{-1}) and exchangeable potassium (0.35 cmol(+)/kg), classifying it as deficient in these crucial nutrients for rice production.

Table 1: Physico-chemical characteristics of the soil (0-30 cm depth) before experimentation and nutrient composition of *Cajanus cajan* biomass.

Parameter	Soil Value	Interpretation	Parameter	Biomass Value
pH (H_2O)	4.4	Acidic	N (%)	2.51
Organic Matter (%)	5.57	High	P (mg kg^{-1})	968.16
Total N (%)	0.156	Medium	K (mg kg^{-1})	5235.78
Avail. P (mg kg^{-1}))	15.29	Low	Ca (mg kg^{-1})	4240.0
Exch. K (cmol(+)/kg)	0.35	Low	Mg (mg kg^{-1})	2721.60
CEC (cmol(+)/kg)	17.10	Moderate		
Texture	Clay Loam	-		

Temporal Dynamics of Nitrogen Nutrition as Assessed by Leaf Color Chart (LCC)

The Leaf Color Chart (LCC) scores revealed significant differences ($p < 0.001$) in the nitrogen nutrition status of the rice plants under different treatments across all growth stages (Table 2). At the early vegetative stage (30 DAS), plants receiving combined mineral and organic amendments (T2 and T3) already showed significantly darker green leaves (LCC scores of 4.5 and 4.6, respectively) compared to the NPK-only treatment (T1, 4.2) and the control (T0, 3.5).

This superiority of the T2 treatment became more pronounced as the season progressed. At the peak

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tillering stage (45 DAS) and during panicle initiation (60 DAS), T2 consistently maintained the highest LCC scores. By the flowering stage (75 DAS), the LCC score for T2 (5.8) was significantly higher than those for T3 (5.5) and T1 (5.3), indicating a more sustained and optimal nitrogen supply throughout the critical reproductive growth phases.

Table 2: Evolution of Leaf Color Chart (LCC) scores of NERICA 8 rice under different fertilization treatments at four growth stages.

Treatment	30 DAS	45 DAS	60 DAS	75 DAS
T0 (Control)	3.5 ± 0.3a	3.7 ± 0.4a	4.1 ± 0.3a	4.3 ± 0.4a
T1 (NPK)	4.2 ± 0.4b	4.8 ± 0.5b	5.2 ± 0.4b	5.3 ± 0.5b
T2 (NPK + Biomass)	4.5 ± 0.3c	5.2 ± 0.4c	5.6 ± 0.3c	5.8 ± 0.4c
T3 (NPK + Urea)	4.6 ± 0.4c	5.0 ± 0.4bc	5.4 ± 0.5b	5.5 ± 0.4b
p-value	< 0.001	< 0.001	< 0.001	< 0.001

Means in the same column followed by different superscript letters are significantly different at $p < 0.05$ according to Tukey's test. DAS: Days After Sowing.

The temporal pattern of nitrogen nutrition, illustrating the consistent superiority of the T2 treatment throughout the growing season, is visually captured in **Figure 3**, which clearly shows the trajectory and significant separation of LCC scores over time.

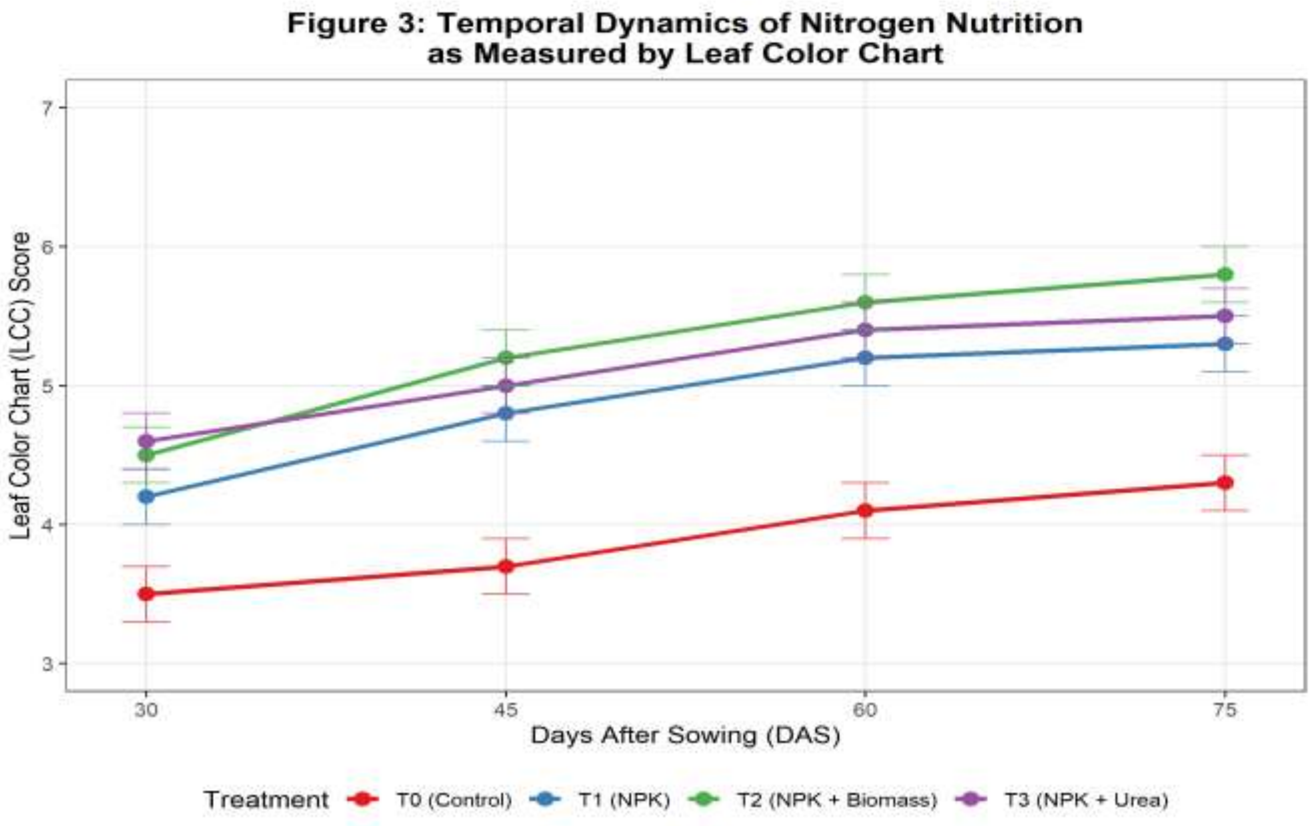

Figure 3: Temporal dynamics of nitrogen nutrition as measured by Leaf Color Chart (LCC) scores under different fertilization treatments at 30, 45, 60, and 75 days after sowing (DAS). Treatments: T0 (Control), T1 (NPK), T2 (NPK + *Cajanus cajan* biomass), T3 (NPK + Urea). Bars represent standard error of the mean.

Distribution of Leaf Color Categories Illustrates Treatment Efficacy

The distribution of plants across the different LCC color categories provides a clearer visual representation of the treatment effects (a suitable bar chart would be ideal here). At 75 DAS, a striking difference was observed:

- **T0 (Control):** The majority of plants (83.3%) exhibited light green to olive green leaves (LCC scores 2-4), a classic symptom of chronic nitrogen deficiency.
- **T1 (NPK):** Only 30.2% of plants achieved the optimal dark green coloration (LCC 5-7), while many remained in the medium green range, suggesting a sub-optimal or declining N status.
- **T3 (NPK+Urea):** Showed an improvement over T1, with 37.0% of plants in the dark green categories.
- **T2 (NPK+Biomass):** Markedly outperformed all others, with 58.3% of its plants displaying the desirable dark green to very dark green leaves (LCC 5-7), underscoring a superior and sustained nitrogen supply.

This stark contrast in the population-level nitrogen status at a critical late growth stage is effectively demonstrated by the distribution of LCC categories presented in Figure 4, where the T2 treatment shows a dominant proportion of plants in the optimal dark green categories.

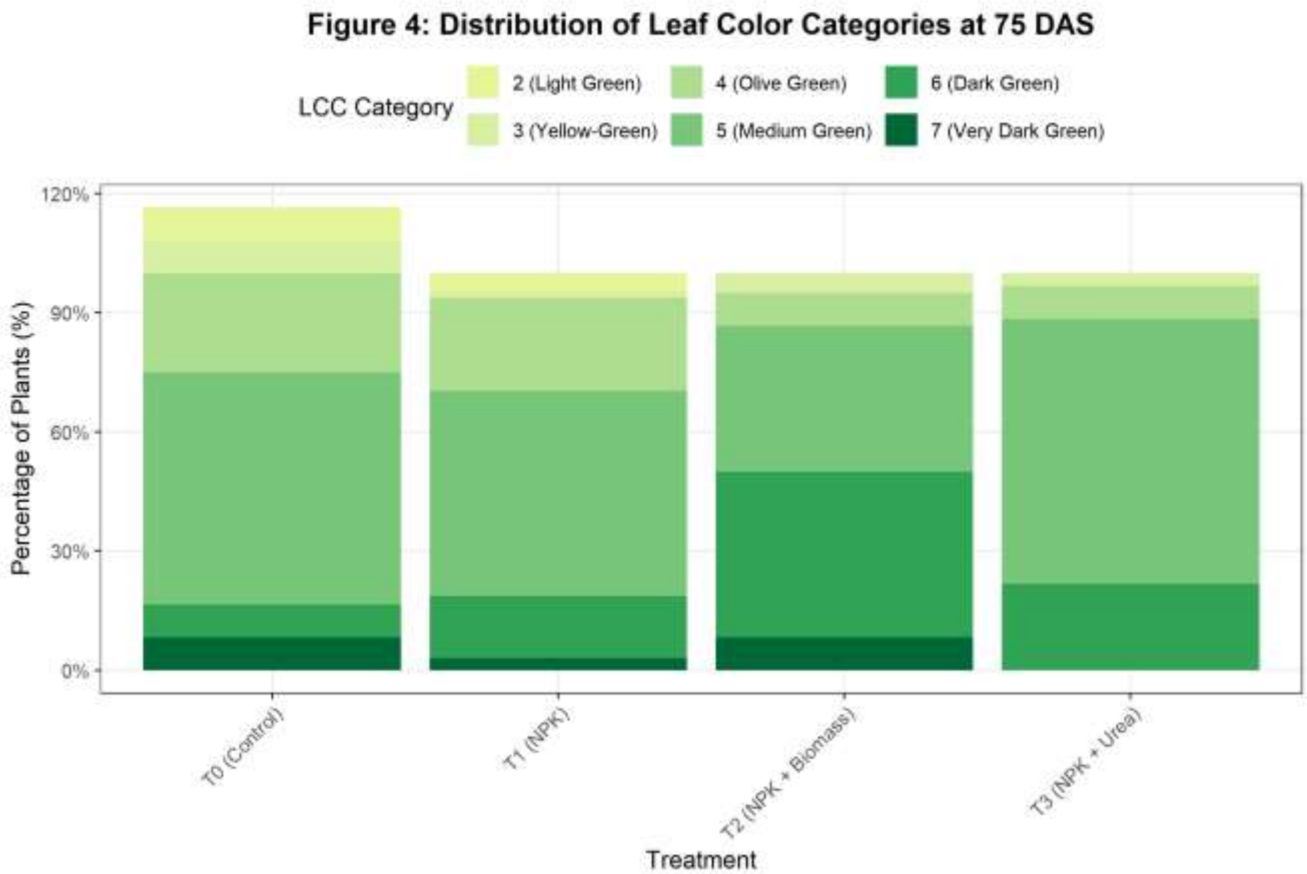

Figure 4: Distribution of rice plants across Leaf Color Chart (LCC) categories at 75 days after sowing (DAS). Categories range from 1 (very light green) to 7 (very dark green). Treatments: T0 (Control), T1 (NPK), T2 (NPK + Biomass), T3 (NPK + Urea).

Superior Nitrogen Nutrition Translates to Enhanced Growth and Yield

The improved nitrogen nutrition in T2, as captured by the LCC, directly translated into significantly better agronomic performance (Table 3). The treatment T2 produced the highest number of panicles per m² (85.1), which was 31% and 21% more than T1 and T3, respectively. Similarly, the number of grains per panicle was greatest in T2 (58.4), significantly outperforming the other treatments.

Most notably, the percentage of filled grains a critical parameter highly dependent on nutrient availability during grain filling was highest in T2 (95.8%). This resulted in a significantly higher 1000-grain weight (27.3 g) and the ultimate grain yield of 5.06 t/ha. The yield advantage of T2 over the sole mineral fertilizer (T1) was 26.8%, demonstrating the concrete benefit of integrating *C. cajan* biomass.

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Table 3: Effect of fertilization treatments on yield and yield components of NERICA 8 rice.

Treatment	Panicles (no./m²)	Grains/Panicle	Filled Grains (%)	1000-Grain Weight (g)	Grain Yield (t/ha)
T0 (Control)	45.3 ± 4.2a	30.2 ± 3.1a	61.5 ± 5.2a	18.3 ± 1.2a	3.60 ± 0.3a
T1 (NPK)	65.2 ± 5.1b	40.2 ± 3.8b	80.3 ± 6.1b	22.1 ± 1.5b	3.99 ± 0.4b
T2 (NPK + Biomass)	85.1 ± 6.3d	58.4 ± 4.9d	95.8 ± 7.3d	27.3 ± 2.1d	5.06 ± 0.5d
T3 (NPK + Urea)	70.3 ± 5.7c	47.0 ± 4.2c	88.8 ± 6.8c	25.2 ± 1.9c	4.39 ± 0.4c
p-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Means in the same column followed by different superscript letters are significantly different at $p < 0.05$ according to Tukey's test.

The significant yield enhancement achieved with the T2 treatment, culminating in a 26.8% advantage over the NPK-only treatment, is clearly depicted in **Figure 5**, where the bar charts with Tukey's letters provide a direct visual confirmation of the statistical differences in grain yield.

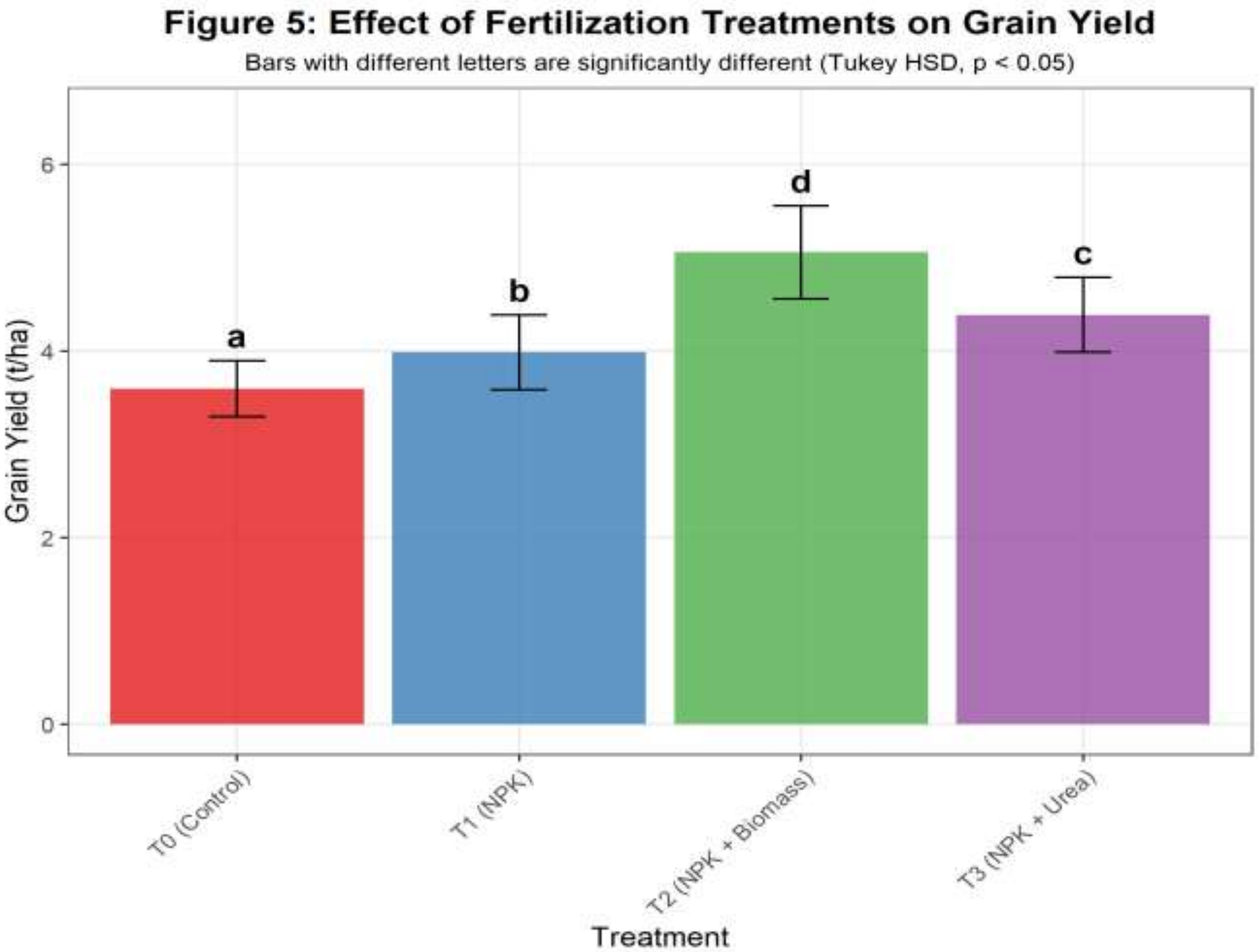

Figure 5: Effect of fertilization treatments on grain yield (t/ha) of NERICA 8 rice. Treatments: T0 (Control), T1 (NPK), T2 (NPK + Cajanus cajan biomass), T3 (NPK + Urea). Bars with different letters indicate significant differences at *p* < 0.05 according to Tukey's HSD test.

Nitrogen Use Efficiency of Fertilization Treatments

The Partial Factor Productivity of Nitrogen (PFPN) highlighted important differences among fertilization strategies and revealed a clear trade-off between nitrogen efficiency and absolute grain yield (Table 4). The NPK-only treatment (T1) exhibited the highest PFPN value (99.8 kg grain kg^{-1} N), reflecting the low mineral nitrogen input rate (40 kg N ha^{-1}) and the efficient short-term utilization of applied nitrogen. However, despite

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this high efficiency, T1 resulted in relatively low grain yield, indicating that nitrogen supply was insufficient to fully exploit the yield potential of the crop.

In contrast, the integrated treatment combining NPK fertilizer with Cajanus cajan biomass (T2) showed a markedly lower PFPN value when calculated using the total nitrogen content of the biomass. This apparent reduction in PFPN should not be interpreted as poor agronomic efficiency. Organic amendments differ fundamentally from mineral fertilizers in that only a fraction of their total nitrogen becomes plant-available during the first cropping season, while the remaining nitrogen contributes to soil organic nitrogen pools and supports longer-term fertility.

Although the total nitrogen content of the applied C. cajan biomass was estimated at 426.7 kg N ha^{-1}, only a limited proportion (commonly estimated at 20–30% under tropical conditions) is expected to mineralize and become available to the crop during the first season. Therefore, PFPN values based on total nitrogen inputs underestimate the functional nitrogen efficiency of organic-based treatments. When interpreted from a systems perspective, the superior grain yield achieved under T2 (5.06 t ha^{-1}) demonstrates that the integrated use of organic and mineral nutrient sources effectively alleviated nitrogen limitations and sustained crop demand throughout critical growth stages.

The NPK + urea treatment (T3) showed intermediate PFPN values (51.0 kg grain kg^{-1} N), reflecting both a higher nitrogen input than T1 and the rapid availability of urea-derived nitrogen. While this treatment improved yield compared to sole NPK application, it remained less productive than the integrated organic–mineral strategy, highlighting the benefits of synchronized nitrogen release provided by biomass incorporation.

Overall, these results underline a key principle of integrated soil fertility management: nitrogen efficiency metrics such as PFPN must be interpreted in conjunction with yield outcomes and nitrogen release dynamics. While sole mineral fertilization maximizes short-term nitrogen efficiency, integrated organic–mineral systems optimize system productivity and sustainability by combining immediate nutrient supply with longer-term soil fertility enhancement.

Table 4: Nitrogen inputs and Partial Factor Productivity from applied Nitrogen (PFPN) for the fertilized treatments.

Treatment	N Application Rate (kg N/ha)	Grain Yield (kg/ha)	PFPN (kg grain/kg N)
T1 (NPK)	40	3990	99.8
T2 (NPK + Biomass)*	40 + 426.7 = 466.7	5060	10.8
T3 (NPK + Urea)	40 + 46 = 86	4390	51.0

***Note**: The nitrogen contribution from Cajanus cajan biomass was calculated based on total N content. However, only a fraction of this nitrogen is expected to be plant-available during the first cropping season. Consequently, PFPN values for organic-based treatments should be interpreted as indicative rather than absolute efficiency metrics.*

LCC Scores as a Predictor of Yield Performance

Pearson correlation analysis revealed strong and significant positive relationships between LCC scores taken at later growth stages and key yield components (Table 5). The LCC score at 75 DAS showed a very strong positive correlation with the final grain yield ($r = 0.79$, $p < 0.01$). It was also significantly correlated with the number of panicles per m^2 ($r = 0.72$), the percentage of filled grains ($r = 0.68$), and the 1000-grain weight ($r = 0.57$). This confirms that the nitrogen status of the plant, as visually assessed by the LCC during the reproductive phase, is a reliable indicator of the final productivity.

Table 5: Pearson correlation coefficients (r) between Leaf Color Chart (LCC) scores at different growth stages and yield parameters.

Yield Parameter	LCC 30 DAS	LCC 45 DAS	LCC 60 DAS	LCC 75 DAS
Panicles per m²	0.58*	0.64*	0.69*	0.72*
Grains per Panicle	0.42	0.51	0.59*	0.63*
Filled Grains (%)	0.47	0.55*	0.62*	0.68*
1000-Grain Weight (g)	0.39	0.46	0.52	0.57*
Grain Yield (t/ha)	0.61*	0.67*	0.74*	**0.79***

***, ** Significant at $p < 0.05$ and $p < 0.01$ probability levels, respectively.**

The robust linear relationship between the LCC score at 75 DAS and grain yield is graphically presented in Figure 6, which shows a strong positive correlation ($R^2 = 0.80$) across all treatments, visually confirming the LCC's practical utility for predicting yield.

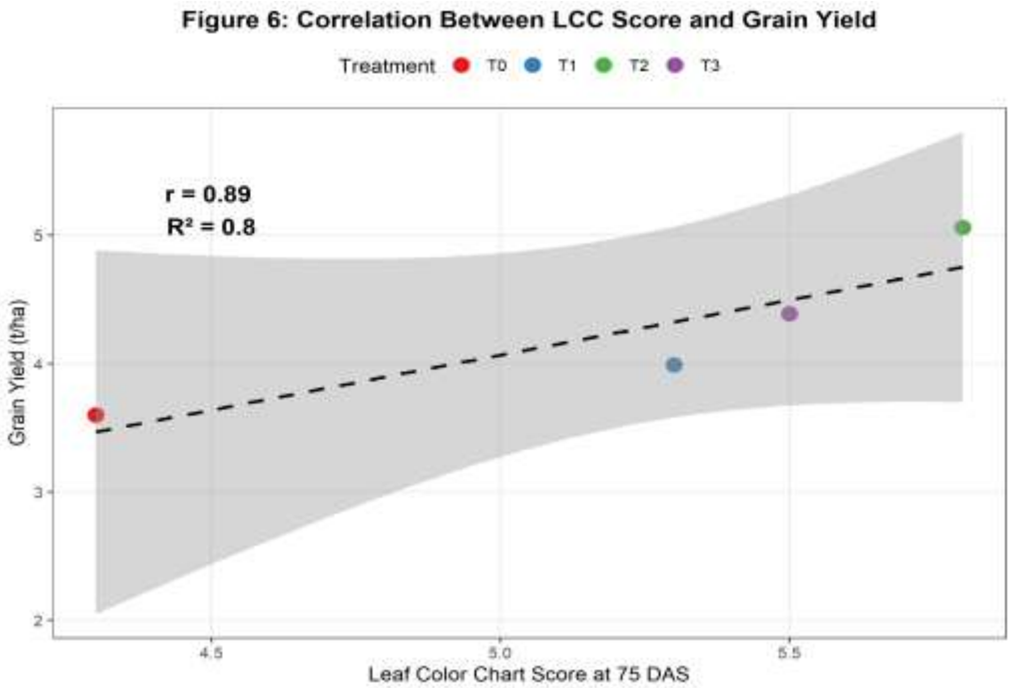

Figure 6. Correlation between Leaf Color Chart (LCC) score at 75 days after sowing (DAS) and grain yield (t/ha) across all treatments. The solid line represents the linear regression fit ($R^2 = 0.80$). Each point corresponds to an experimental unit S

DISCUSSIONS

This study provides compelling evidence that the integrated application of *Cajanus cajan* biomass with mineral NPK fertilizer creates a superior nutrient management regime for rainfed rice, enhancing both nitrogen nutrition and grain yield more effectively than mineral fertilizers alone. The sustained nitrogen dynamics observed in the T2 treatment, as captured by the consistently higher LCC scores, confirm our hypothesis and highlight the multifaceted value of legume-based amendments in smallholder systems.

The significantly higher LCC scores in the T2 treatment from tillering through flowering indicate a more consistent nitrogen supply, attributable to the gradual mineralization of the high-quality *C. cajan* biomass. This synchronization of nitrogen release with crop demand likely mitigated the rapid losses common with urea in the acidic soils of our study area (Shang et al., 2025). Our findings resonate with recent work in West Africa; for instance, a study in Nigeria by Uzoh et al. (2019) found that incorporating *Lablab purpureus* biomass sustained soil nitrogen availability for a subsequent maize crop more effectively than urea. Similarly, research in Ghana by Fontanetti et al. (2024) demonstrated that maize intercropped with pigeon pea maintained higher leaf chlorophyll levels during grain filling, underscoring the role of legumes in providing sustained late-season nitrogen.

The superior agronomic performance of T2, culminating in a 26.8% yield advantage, can be powerfully interpreted through the lens of Integrated Soil Fertility Management (ISFM). This paradigm emphasizes the use of organic resources as a "resource complex" to improve the efficiency of mineral inputs by enhancing the soil's physical, chemical, and biological environment (Mugwe et al., 2019). In our study, *Cajanus cajan* biomass acted as such a complex. Beyond nitrogen, its decomposition releases organic acids that chelate fixed phosphorus, a critical mechanism in the highly P-fixing soils of SSA (Sakib et al., 2025). Furthermore, the addition of organic matter improves soil structure and water retention (Demo & Bogale, 2024), creating a more favorable rhizosphere. This multipartite benefit aligns with findings from Malawi, where pigeon pea rotations improved both nitrogen supply and crop resilience to mid-season drought (Snapp et al., 2019).

A critical consideration for adoption is the feasibility of producing 17 t/ha of biomass. This quantity, while substantial, can be attained through context-appropriate strategies. Farmers can utilize residual biomass after grain harvest, a currently underutilized by-product (Ojiewo et al., 2018), or establish high-density "biomass banks" on field boundaries to generate organic matter with minimal opportunity cost (Muoni et al., 2019; Snapp et al., 2019). The primary constraint is the labor for harvesting and incorporation. However, this must be weighed against the recurring financial cost of mineral fertilizers, a major barrier for smallholders (Tittonell & Giller, 2013). The 26.8% yield increase demonstrated here suggests a significant economic return, though a detailed cost-benefit analysis is a critical next step for validation.

The environmental implications of this integrated approach are substantial. The slow-release nature of nitrogen from the biomass inherently reduces the risk of leaching and volatilization, common fates of urea-N that contribute to greenhouse gas emissions (Motasim et al., 2024). Moreover, the regular addition of organic carbon is a direct pathway for soil carbon sequestration, helping to mitigate climate change while building long-term productivity (Zong et al., 2025).

It is important to acknowledge the limitations of this research. First, the study was conducted over a single cropping season, which precludes assessment of the long-term residual effects on soil carbon and fertility. Second, the 17 t/ha application rate, while effective, requires optimization for logistical and economic viability. Finally, the lack of direct measurement of soil microbial community shifts or nitrogen leaching means the mechanistic underpinnings of the observed benefits are inferred rather than quantified.

CONCLUSION AND RECOMMENDATIONS

This study conclusively demonstrates that the integrated application of *Cajanus cajan* biomass with mineral NPK fertilizer provides a more stable and efficient nitrogen supply for rainfed rice, leading to superior growth and yield compared to the use of mineral fertilizers alone. The Leaf Color Chart (LCC) proved to be an effective and reliable tool for monitoring this dynamic, with the treatment receiving *C. cajan* biomass (T2) maintaining significantly higher LCC scores throughout the critical growth stages. The strong positive correlation between LCC scores at flowering and final grain yield underscores the LCC's utility not just for urea management, but also for assessing the performance of organic soil amendments. The 26.8% yield advantage of the integrated system (T2) over the NPK-only treatment (T1) validates the role of *C. cajan* as a key resource for sustainable intensification, improving nitrogen use efficiency and overall system productivity on nutrient-depleted, acidic soils.

To translate these findings into actionable steps, we recommend that smallholder farmers adopt the integrated application of *Cajanus cajan* biomass (17 t/ha) with a moderate rate of NPK fertilizer (200 kg/ha) to enhance nitrogen availability and boost rainfed rice yields sustainably and cost-effectively. The consistent use of the Leaf Color Chart should be promoted as a simple monitoring tool to visualize the benefits of this approach and guide in-season management decisions. For policymakers and extension services, this entails promoting the cultivation of dual-purpose *Cajanus cajan* and developing support systems to facilitate farmers' access to seeds and technical knowledge on biomass management. Future research should focus on conducting long-term studies to quantify the soil health benefits, performing detailed economic analyses to validate profitability, and optimizing application protocols for different agro-ecological zones across Sub-Saharan Africa.

Data Availability Statement

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

Conflicts Of Interest

The authors declare that they have no conflicts of interest.

Author Contributions

Bertrand Kenzong, the corresponding author and Elza Chirelle Segnou Mbougna, conceptualized and conducted the research, collected data, analysed data, and drafted and edited the original manuscript. Georges Simplice Kameni Kouedeu, Joseph Zetekoouang Guepi, Primus Azinwi Tamfuh, Elza Chirelle Segnou Mbougna and Emile Temgoua contributed to manuscript edition. All the authors read and approved to the final version of the manuscript.

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