

Effects of Nitrogen Management Practices on Nutrient Use Efficiency, Growth, and Biomass Production of Lowland Rice (*Oryza sativa* L.)

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Abstract

Rice (*Oryza sativa* L.) productivity is often constrained by low nitrogen use efficiency (NUE), leading to reduced yields and increased environmental nitrogen losses. This study evaluated the effects of different nitrogen management practices on the growth, yield, biomass accumulation, and NUE of lowland rice under screen house conditions at the Federal University of Agriculture, Abeokuta, Nigeria. The experiment was arranged in a Completely Randomized Design (CRD) with seven nitrogen treatments: control, conventional split application, phenology-based split application, slow-release nitrogen, green manure + reduced nitrogen, foliar nano-urea, and poultry manure + reduced nitrogen, each replicated three times. Nitrogen management practices did not significantly affect plant height during the early growth stages but showed significant differences at 14 weeks after transplanting (WAT), where conventional split application (197.1 cm) and slow-release nitrogen (196.1 cm) produced the tallest plants compared with the control (153.1 cm). Tiller production differed significantly at 8–12 WAT, with poultry manure + reduced nitrogen producing the highest number of tillers. Yield components, including panicle length, grains per panicle, 1000-grain weight, and grain yield per plant, were not significantly affected ($p \geq 0.05$), although conventional split application recorded the highest numerical grain yield. Partial factor productivity was significantly improved by phenology-based split application (23.83) and conventional split application (21.83). Poultry manure + reduced nitrogen also produced the highest whole-plant wet (381.7 g) and dry (134.77 g) biomass. These findings indicate that split nitrogen application and integrated organic-inorganic nitrogen management can improve NUE and biomass production, contributing to more sustainable lowland rice production.

Keywords: Biomass Production, Lowland Rice, Nitrogen Management, Nitrogen Use Efficiency.

Introduction

Rice (*Oryza sativa* L.) is one of the most important staple crops globally, providing a primary source of calories for more than half of the world's population and contributing significantly to food security, particularly in Asia and sub-Saharan Africa. With increasing population pressure and changing climatic conditions, the demand for rice continues to rise, necessitating sustainable intensification of production systems (Jain et al., 2023). Lowland rice ecosystems, which account for a substantial proportion of global rice production, are

characterized by flooded conditions that support high yield potential but also present unique agronomic challenges (Dobermann and Fairhurst, 2000; Chivenge et al., 2021).

Nitrogen (N) remains the most limiting nutrient in lowland rice production systems and is a key determinant of crop growth, yield, and grain quality (Wang et al., 2022). Adequate nitrogen supply promotes tillering, leaf area development, and photosynthetic capacity, ultimately influencing biomass accumulation and yield formation (He et al., 2024; Sung et al., 2023). However, nitrogen use efficiency (NUE) in rice systems is generally low—often below 40%—due to substantial losses through ammonia volatilization, denitrification, leaching, and surface runoff. These losses not only reduce the effectiveness of applied fertilizers and increase production costs but also contribute to environmental concerns such as greenhouse gas emissions, particularly nitrous oxide (N₂O), and contamination of water bodies (Cassman et al., 2002).

The flooded conditions typical of lowland rice fields create a complex soil–water environment that accelerates nitrogen transformations. Under anaerobic conditions, nitrogen dynamics are highly variable, with rapid conversion between ammonium and gaseous forms, making applied nitrogen particularly vulnerable to losses (Farooq et al., 2022). These processes are strongly influenced by management practices such as fertilizer source, rate, timing, placement method, and water management, as well as by soil properties and climatic factors. Consequently, optimizing nitrogen management is critical for improving NUE while maintaining or enhancing rice productivity (Wang et al., 2022; Yu, et al, 2022).

In recent years, several nitrogen management strategies have been developed to address the challenges of low nitrogen use efficiency in rice systems. These include split nitrogen application, deep placement techniques such as urea briquettes, use of enhanced-efficiency fertilizers and site-specific nutrient management approaches (Zhu et al., 2019; Chivenge et al., 2021; Wang et al., 2022; Kumar et al., 2024). Emerging research also highlights the role of precision agriculture tools and decision-support systems in optimizing nitrogen application based on real-time crop needs. While these strategies have shown promise in improving NUE and reducing environmental losses, their effectiveness is often site-specific and influenced by interactions among soil characteristics, climate variability, water regime, and rice genotype (Peng et al., 2006; Chivenge et al., 2021; Wang et al., 2022).

Objective

To determine and compare nitrogen use efficiency indices under varying nitrogen management practices in lowland rice production systems.

Specific Objectives

1. To assess the influence of nitrogen management practices on biomass accumulation (wet and dry matter production) of lowland rice.
2. To evaluate the effects of different nitrogen management practices on yield and yield components of lowland rice.

3. To determine and compare nitrogen use efficiency indices under different nitrogen management practices in lowland rice production systems.

Null Hypothesis (H_0)

Nitrogen management practices have no significant effect on nutrient use efficiency, growth, biomass production, or yield of lowland rice (*Oryza sativa* L.).

Alternative Hypothesis (H_1)

Nitrogen management practices have a significant effect on nutrient use efficiency, growth, biomass production, and yield of lowland rice (*Oryza sativa* L.).

Literature Review

Rice (*Oryza sativa* L.) is the staple food for more than half of the global population and continues to play a critical role in food security, particularly in Asia and sub-Saharan Africa (Lee, 2021; Kunwar et al., 2025). Nitrogen (N) is the most important yield-limiting nutrient in rice cultivation and is therefore applied extensively in lowland rice production systems to sustain crop growth and productivity (Wang et al., 2022; Kunwar et al., 2025). Despite its indispensable role, nitrogen use efficiency (NUE) in rice remains relatively low, with recovery efficiencies commonly ranging from 30–50% because substantial portions of applied nitrogen are lost through ammonia volatilization, denitrification, runoff, and leaching processes (Alam et al., 2025). These nitrogen losses not only reduce crop productivity and fertilizer profitability but also contribute significantly to environmental challenges such as greenhouse gas emissions, eutrophication, and water pollution (Alam et al., 2025; Wang et al., 2022). Consequently, improving nitrogen management has become a major objective of sustainable rice production systems worldwide. Recent studies have demonstrated that practices such as site-specific nutrient management, split nitrogen application, deep placement of urea, controlled-release fertilizers, and precision nitrogen management technologies can simultaneously improve grain yield, enhance nutrient use efficiency, and reduce environmental impacts associated with rice cultivation (Azhar et al., 2025; Kunwar et al., 2025; Wang et al., 2022).

Controlled-Release Fertilizers

Controlled-release fertilizers represent an advanced approach to nitrogen management that aims to synchronize nutrient release with crop demand throughout the growing season. These fertilizers use various technologies to slow down the release of nitrogen, including coating materials, chemical modifications, or incorporation into organic matrices. Sulfur-coated urea and polymer-coated urea are common examples that release nitrogen gradually over periods ranging from 40 to 120 days (Tian et al., 2018).

The primary advantage of controlled-release fertilisers is the potential for single-application management, eliminating the need for multiple fertiliser events. A comprehensive meta-analysis reported that controlled-release fertilisers increased rice

yields by 6–12% and improved nitrogen use efficiency from 35.7% to 44.9% compared to conventional urea (Govil et al., 2024). In flooded rice systems, controlled-release fertilisers reduce both volatilisation and denitrification losses by releasing nitrogen slowly into the reduced soil zone, where it is protected from loss mechanisms. Recent studies have shown that controlled-release urea can improve nitrogen recovery efficiency by 30–50% and reduce greenhouse gas emissions by 20–25% during rice growing seasons (Zhao et al., 2023).

Despite their agronomic benefits, the adoption of controlled-release fertilizers in developing countries, including Nigeria, remains limited due to their higher cost, typically 2–3 times more expensive than conventional urea. Economic feasibility depends on whether the combination of labour savings, reduced fertilizer rates, and yield improvements justifies the premium price. Research conducted in 2023–2024 suggests that blending controlled-release fertilizers with conventional urea at ratios of 50:50 or 70:30 can provide an economically viable compromise that maintains most efficiency benefits while reducing costs (Wang et al., 2024). However, for resource-constrained smallholder farmers, the initial cost often presents a significant barrier to adoption.

Influence of Rice Varieties on Nitrogen use Efficiency

Genotypic variation significantly influences nitrogen use efficiency (NUE) in rice. Modern rice cultivars differ considerably in their capacity for nitrogen uptake, assimilation, remobilization, and grain production, resulting in substantial variation in NUE among genotypes (Hu et al., 2023; Kunwar et al., 2025). High-NUE rice varieties typically possess more efficient root architectures, enhanced nitrogen transport systems, superior nitrogen assimilation pathways, and greater physiological efficiency, enabling them to maintain high productivity under reduced nitrogen inputs (Salama et al., 2024; Wang et al., 2024). Recent advances in molecular breeding and genomics have identified numerous genes, quantitative trait loci (QTLs), and regulatory networks associated with nitrogen uptake, transport, assimilation, remobilization, and utilization in rice, thereby providing new opportunities for developing nitrogen-efficient cultivars through marker-assisted selection and genome-editing technologies (Hu et al., 2023; Fiaz et al., 2021; Salama et al., 2024). The integration of nitrogen-efficient genotypes with improved agronomic management practices, including site-specific nutrient management and precision nitrogen application, offers considerable potential for enhancing NUE and promoting sustainable rice production in lowland ecosystems (Kunwar et al., 2025). However, genotype-by-environment interactions continue to influence the expression of NUE-related traits across diverse agroecological conditions, posing challenges for the widespread adoption and consistent performance of nitrogen-efficient rice varieties (Wang et al., 2024; Kunwar et al., 2025).

Materials and Methods

Experimental Site

The study was conducted under screen house conditions at the Centre of Excellence in Agricultural Development and Sustainable Environment (CAEDESE), Federal University of

Agriculture, Abeokuta, Nigeria. Topsoil (0–20 cm) classified as sandy loam was collected from the FADAMA experimental field, air-dried, sieved (2 mm), homogenized, and bulked to ensure uniformity. Composite soil samples were analyzed for baseline physical and chemical properties prior to experimentation.

Experimental Design and Treatments

The experiment was arranged in a Completely Randomized Design (CRD) with seven nitrogen management treatments and three replications (21 experimental units). All pots received a uniform basal application of 40 kg P₂O₅ ha⁻¹ (single superphosphate) and 40 kg K₂O ha⁻¹ (muriate of potash) to ensure nitrogen was the primary limiting nutrient.

Treatments included:

- N₁: Control (0 N)
- N₂: Conventional split application (120 kg N ha⁻¹; 2 splits)
- N₃: Phenology-based split application (120 kg N ha⁻¹; 3 splits)
- N₄: Polymer-coated slow-release urea (120 kg N ha⁻¹)
- N₅: Green manure + reduced N
- N₆: Foliar nano-urea (three sprays)
- N₇: Poultry manure + reduced mineral N

Planting Materials and Soil Preparation

Rice variety FARO 44 was sourced from SeedCo, Nigeria. Pots (11 L) were filled with 10 kg of prepared soil and arranged under CRD arrangement.

Nursery Establishment and Transplanting

Seeds were pre-germinated by soaking for 24 hrs and incubating for 48 hrs achieving ~99% germination. Seedlings were raised for 21 days under nursery conditions before transplanting. Three seedlings were transplanted per pot and later thinned to two. Pots were maintained at ~70% field capacity initially and flooded (3–5 cm water depth) one day after transplanting until two weeks before maturity.

Data Collection

Data were collected at two-week intervals and at maturity.

Growth parameters

- Plant height (cm)
- Number of tillers
- Leaf area (cm²)
- Chlorophyll content (SPAD value)

Yield components

- Panicle length
- Number of grains per panicle
- 1000-grain weight

- Grain yield per pot
- Straw yield
- Harvest index

Nutrient use Efficiency Indices

The following were computed:

- **Nitrogen Use Efficiency (NUE):** $NUE = \text{Grain yield} / N \text{ applied}$
- **Agronomic Efficiency (AE):** $AE = (Y_f - Y_o) / N$
- **Recovery Efficiency (RE):** $RE (\%) = [(U_f - U_o) / N] \times 100$
- **Physiological Efficiency (PE):** $PE = (Y_f - Y_o) / (U_f - U_o)$
- **Partial Factor Productivity (PFP):** $PFP = Y_f / N$

Where Y_f = fertilized yield, Y_o = control yield, U_f = N uptake in fertilized plots, U_o = N uptake in control, and N = applied nitrogen.

Physical and Chemical Properties of Soil.

Properties	Value
Sand (%)	83.96
Silt (%)	5.72
Clay (%)	10.33
Textural class	Sandy loam
pH	7.55
N (%)	0.259
Org. C (%)	0.99
Org. M (%)	1.72
P(mg/kg)	18.62
Ex. A(mEq/100g)	0.62
Na(mg/kg)	0.331
K(mg/kg)	0.588

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using Genstat (12th edition). Treatment means were separated using the standard error of difference (SED) at the 5% probability level.

Results

The results show that nitrogen management practices had no significant ($p \leq 0.05$) effect on plant height at the early vegetative stage (Table 1). This suggests that, during the early and mid-growth stages, plant height was relatively similar across all treatments regardless of the nitrogen management strategy applied. However, at 14 WAT, a significant difference ($p \leq 0.05$) was observed among treatments (SED = 14.32). This indicates that nitrogen management began to influence plant height at the later growth stage. At 14 WAT, conventional split (197.1 cm) and slow-release nitrogen (196.1 cm) treatments produced the

tallest plants while the control treatment recorded the lowest plant height (153.1 cm), indicating the importance of nitrogen application.

The emergence of significant differences only at 14 WAT suggests that the effect of nitrogen management becomes more pronounced during the later stages of crop development, likely due to increased nutrient demand for reproductive growth and biomass accumulation.

Table 1: Effects of nitrogen management practices on plant height at different growth stages

Treatment	2 WAT	4 WAT	6 WAT	8 WAT	10 WAT	12 WAT	14 WAT
Control	70.7	95.9	107.2	114.2	142.8	171.7	153.1
Conventional split	68.3	80.2	114.3	121.5	159.4	196.2	197.1
Phenology-based split	60.3	83.6	109.3	116.0	164.0	193.2	185.3
Slow-release nitrogen	67.7	90.2	102.9	114.1	145.0	196.2	196.1
Green manure + reduced N	62.3	95.3	111.5	117.6	149.4	173.9	192.2
Foliar nano-urea	70.0	99.7	110.0	117.4	143.4	170.9	164.6
Poultry manure + reduced N	65.7	95.1	111.8	122.4	153.5	170.3	166.1
SED	ns	ns	ns	ns	ns	ns	14.32*

Note.

WAT = weeks after transplanting; SED = standard error of the difference; ns = not significant at $p \leq .05$; * indicates significant difference at $p \leq .05$.

Table 2 shows the influence of different nitrogen management practices on number of tillers from 2 to 14 weeks after transplanting (WAT). Tiller number is an important growth parameter because it directly contributes to the potential number of productive panicles and ultimately grain yield.

At the early growth stages (2, 4, and 6 WAT), there were no significant differences among treatments. Although numerical variations existed, the nitrogen management practices did not significantly influence tiller production during the early establishment phase of the crop.

By 8 WAT, significant differences in number of tiller were observed. Poultry manure + reduced N produced the highest number of tillers at 8 WAT (22.67 tillers), followed by the Conventional split application (18.00 tillers) and Slow-release nitrogen (15.67 tillers). The control treatment produced the fewest tillers (8.67 tillers). This suggests that integrating poultry manure with reduced inorganic nitrogen enhanced nutrient availability and stimulated vigorous vegetative growth.

At 10 WAT, the differences among treatments remained significant (SED = 3.78). The Poultry manure + reduced N treatment again maintained the highest number of tillers (15.33), closely followed by Conventional split nitrogen application (15.00). The control and

foliar nano-urea treatments recorded comparatively lower tiller numbers (4.67 and 4.00, respectively). The sustained tillering observed in poultry manure-amended plots may be attributed to the gradual release of nutrients and improved soil fertility conditions.

At 12 WAT, highly significant differences were again observed ($SED = 1.522$). The Poultry manure + reduced N treatment produced the highest tiller number (9.00), while Slow-release nitrogen (8.00), Phenology-based split (7.00), and Green manure + reduced N (7.33) also maintained relatively higher tiller counts compared with the control and foliar nano-urea treatments (3.33 each).

At 14 WAT, no significant differences were detected among treatments, although the Poultry manure + reduced N treatment still numerically recorded the highest tiller count (9.67), followed by Conventional split (7.33). The decline in tiller number at later stages across treatments could be due to natural tiller senescence and competition among tillers as the crop approached maturity.

Table 2: Effects of nitrogen management practices on number of tillers at different growth stages

Treatment	2 WAT	4 WAT	6 WAT	8 WAT	10 WAT	12 WAT	14 WAT
Control	2.00	6.67	9.33	8.67	4.67	3.33	4.33
Conventional split	2.67	9.33	12.67	18.00	15.00	7.00	7.33
Phenology-based split	1.33	5.67	12.33	10.67	10.00	7.00	5.67
Slow-release nitrogen	2.00	8.00	10.00	15.67	8.33	8.00	6.33
Green manure + reduced N	2.67	8.00	8.67	14.00	6.33	7.33	6.33
Foliar nano-urea	3.00	9.00	9.00	9.33	4.00	3.33	3.33
Poultry manure + reduced N	2.67	12.00	12.33	22.67	15.33	9.00	9.67
SED	ns	ns	ns	3.11**	3.78*	1.522**	ns

Note.

WAT = weeks after transplanting; ns = not significant at $p \leq .05$; * and ** = significance at $p \leq .05$ and $p \leq .01$, respectively.

Nutrient use efficiency indices showed varying responses to nitrogen management practices (Table 3). However, most of the parameters; agronomic efficiency (AE), physiological efficiency (PE), and recovery efficiency (RE) were not significantly affected ($p \geq 0.05$) by nitrogen management treatments. This suggests that although numerical differences existed among treatments, they were not statistically reliable.

However, partial factor productivity (PFP) was highly significant ($p < 0.001$) across treatments, indicating that nitrogen management practices had a strong effect on this efficiency index.

For PFP, the phenology-based split (23.83) and conventional split (21.83) nitrogen applications recorded the highest values and were statistically similar, both outperforming most other treatments while the control (0.00) recorded the lowest value.

Table 3. Effect of Nitrogen Management Practices on Nutrient Use Efficiency Indices of Lowland Rice Variety

Treatment	Agronomic Efficiency	Physiological Efficiency	Partial Factor Productivity	Recovery Efficiency	Nitrogen Use Efficiency
Control	0.00	0.00	0.00 ^c	0.00	0.00
Conventional split	10.57	1.07	21.83 ^a	10.57	10.57
Phenology-based split	5.33	0.70	23.83 ^a	5.07	5.33
Slow-release nitrogen	3.37	2.83	8.97 ^b	3.22	3.37
Green manure + reduced N	1.43	7.37	3.27 ^{bc}	1.16	1.43
Foliar nano-urea	-0.17	-5.00	4.23 ^{bc}	0.47	-0.17
Poultry manure + reduced N	1.20	5.30	4.23 ^{bc}	1.20	1.20
SED	ns	ns	3.3 ^{**}	ns	ns

Notes

- ns = not significant;
- ** = significant at $p \leq 0.01$.

Table 4 presents the effects of different nitrogen management (NM) practices on yield and yield-related parameters, including panicle length (PL), number of panicles per plant (PP), 1000-grain weight, grain yield per plant (GY_P), and number of grains per panicle (G_P). The analysis of variance showed that nitrogen management practices did not significantly affect any of the measured yield parameters, as indicated by the non-significant F-probability values ($p > 0.05$) for all variables. This suggests that the various nitrogen management strategies produced statistically similar responses for the yield traits evaluated.

Table 4. Effect of Nitrogen Management Practices on Yield and Yield Components of Lowland Rice variety

Nitrogen Management (NM)	Panicle Length	Panicle per plant	1000 Grain Weight	Grain Yield per Plant	Grains per Panicle
Control	37.40	4.33	36.00	15.73	149.0
Conventional split	33.67	6.33	38.00	30.53	196.7
Phenology-based split	38.23	4.67	34.67	20.53	177.0
Slow-release nitrogen	33.57	5.00	34.00	25.13	174.0
Green manure + reduced N	34.17	5.67	32.67	27.10	173.0
Foliar nano-urea	37.27	3.67	38.00	21.13	207.3

Nitrogen Management (NM)	Panicle Length	Panicle per plant	1000 Grain Weight	Grain Yield per Plant	Grains per Panicle
Poultry manure + reduced N	37.03	6.33	34.67	22.03	194.3
SED ($p \leq 0.05$)	ns	ns	ns	ns	ns

Note:

- ns = not significant.

Table 5 describes the effects of different nitrogen management (NM) practices on wet weight parameters, including whole plant wet weight (WWH), wet weight of leaves (WWL), wet weight of roots (WWR), and wet weight of stems (WWS).

The analysis of variance revealed that nitrogen management practices significantly influenced whole plant wet weight (WWH) and wet weight of roots (WWR), whereas wet weight of leaves (WWL) and wet weight of stems (WWS) were not significantly affected.

For whole plant wet weight (WWH), significant differences were observed among treatments ($p = 0.040$). Poultry manure + reduced N recorded the highest whole plant wet weight (381.7 g), followed closely by conventional split (323.0 g) and green-manure + reduced N (322.4 g). The lowest value was obtained in foliar-nano urea (159.3 g). The higher wet biomass accumulation under poultry manure + reduced N suggests improved nutrient availability and enhanced vegetative growth, which promoted greater water retention and tissue development.

Wet weight of leaves (WWL) did not differ significantly among treatments ($p = 0.275$), although numerical differences existed. Poultry manure + reduced N recorded the highest leaf wet weight (34.60 g), followed by conventional (31.67 g) and green manure + reduced N (29.17 g), while foliar-nano urea and slow-release N produced the lowest values (17.80 g and 18.00 g, respectively). The lack of statistical significance indicates that leaf water accumulation was relatively similar across nitrogen management practices.

Nitrogen management practices significantly affected wet weight of roots (WWR) ($p = 0.011$). Poultry manure + reduced N produced the highest root wet weight (151.40 g), followed by conventional (122.70 g) and green-manure + reduced N (120.80 g). Conversely, foliar-nano urea recorded the lowest root wet weight (32.80 g). The increased root wet biomass under Poultry manure + reduced N may reflect improved root growth and enhanced nutrient uptake efficiency.

For wet weight of stems (WWS), no significant differences were detected among treatments ($p = 0.137$). Nevertheless, poultry manure + reduced N numerically recorded the highest stem wet weight (192.6 g), while NM6 had the lowest value (95.2 g). Although differences were not statistically significant, the trend suggests that some nitrogen treatments enhanced stem growth and moisture accumulation.

Table 5. Effects of Nitrogen Management Practices on Wet Weight Parameters

Nitrogen Management (NM)	Whole Plant Wet Weight	Wet Weight Leaf	Wet Weight Root	Wet Weight Shoot
Control	209.0 ^{bc}	25.73	53.80 ^{cd}	105.0
Conventional split	323.0 ^{ab}	31.67	122.70 ^{ab}	132.5
Phenology-based split	256.2 ^{abc}	27.53	110.40 ^{abc}	116.0
Slow-release nitrogen	264.5 ^{abc}	18.00	84.33 ^{bcd}	137.3
Green manure + reduced N	322.4 ^{ab}	29.17	120.80 ^{ab}	164.4
Foliar nano-urea	159.3 ^c	17.80	32.80 ^d	95.2
Poultry manure + reduced N	381.7 ^a	34.60	151.40 ^a	192.6
SED ($p \leq 0.05$)	59.4 [*]	ns	27.37 [*]	ns

Notes:

- ns = not significant;
- * = significant at $p \leq 0.05$.

Table 6 shows the effects of different nitrogen management (NM) practices on dry matter accumulation in different plant parts, namely dry weight of roots (DWR), leaves (DWL), stems (DWS), and total plant dry weight (DWW). The analysis of variance revealed varying degrees of significance among the measured parameters.

For dry weight of roots (DWR), nitrogen management practices did not significantly influence root dry matter production ($p = 0.140$). Although statistical differences were not observed, numerical variations existed among treatments. Poultry manure + reduced N recorded the highest root dry weight (47.17 g), while control produced the lowest value (12.43 g). The absence of significant differences suggests that root biomass accumulation was relatively stable across nitrogen management treatments.

In contrast, dry weight of leaves (DWL) was significantly affected by nitrogen management practices ($p = 0.022$). Poultry manure + reduced N produced the highest leaf dry weight (27.00 g), followed by phenology- based split (21.80 g) and green-manure + reduced N (18.43 g). The lowest leaf dry weights were observed under foliar-nano urea (10.10 g) and control (11.10 g). The increased leaf biomass under poultry manure + reduced N may indicate enhanced nitrogen availability, which promoted vegetative growth and leaf development.

Similarly, dry weight of stems (DWS) was highly significantly influenced by nitrogen management practices ($p = 0.005$). Poultry manure + reduced N recorded the highest stem dry weight (60.60 g), closely followed by phenology- based split (59.33 g) and Conventional split (55.50 g). The lowest stem dry weights were recorded in control (24.90 g) and foliar-nano urea (25.67 g). This result suggests that improved nitrogen management enhanced assimilate production and stem growth.

Total dry weight (DWW) also showed highly significant differences among treatments ($p = 0.003$). Poultry manure + reduced N produced the highest total dry matter accumulation (134.77 g), followed by phenology- based split (119.00 g) and Conventional split (106.53 g). Conversely, control and foliar-nano urea recorded the lowest total dry weights, with values of 48.43 g and 49.97 g, respectively. The superior performance of poultry manure + reduced N indicates its effectiveness in improving overall biomass production and nutrient utilization efficiency.

Table 6. Effects of Nitrogen Management Practices on Dry Weight Parameters of lowland rice variety

Nitrogen Management (NM)	Dry Weight of Root	Dry Weight of Leaf	Dry Weight of Stem	Whole Dry Weight
Control	12.43	11.10 ^c	24.90 ^b	48.43 ^c
Conventional split	34.03	16.47 ^{bc}	55.50 ^a	106.53 ^{ab}
Phenology-based split	36.30	21.80 ^{ab}	59.33 ^a	119.00 ^{ab}
Slow-release nitrogen	27.17	13.00 ^{bc}	41.67 ^{ab}	81.90 ^{bc}
Green manure + reduced N	31.53	18.43 ^{abc}	46.60 ^a	96.67 ^{ab}
Foliar nano-urea	14.17	10.10 ^c	25.67 ^b	49.97 ^c
Poultry manure + reduced N	47.17	27.00 ^a	60.60 ^a	134.77 ^a
SED ($p \leq 0.05$)	ns	4.40 [*]	8.74 ^{**}	18.33 ^{**}

Notes:

- ns = not significant; * = significant at $p \leq 0.05$; ** = significant at $p \leq 0.01$.

Discussion

The present study showed that nitrogen management practices significantly influenced vegetative growth, biomass accumulation, and partial factor productivity of lowland rice, although most yield components and nutrient use efficiency indices were not significantly affected. These findings are consistent with previous studies which reported that appropriate nitrogen management improves rice growth and nutrient utilization efficiency, especially under flooded lowland conditions where nitrogen losses are usually high (Peng et al., 2006; Wang et al., 2022).

The absence of significant differences in plant height during the early growth stages suggests that rice plants relied partly on seed nutrient reserves and residual soil nitrogen during establishment. In the present study, significant differences in plant height observed at 14 WAT under conventional split and slow-release nitrogen treatments indicate that continuous nitrogen availability during later growth stages enhanced stem elongation and vegetative growth. This result agrees with the findings of He et al. (2024), who observed improved rice growth and photosynthetic performance when nitrogen was supplied in synchrony with crop demand. Similarly, Peng et al. (2006) reported that split nitrogen application improved crop growth by reducing nitrogen losses and increasing nitrogen availability during critical growth stages.

Tiller production was significantly influenced by nitrogen management practices during the active vegetative phase, particularly under poultry manure combined with reduced

inorganic nitrogen. The superior tillering observed under this treatment agrees with the findings of Chivenge et al. (2021), who reported that integrated organic–inorganic nutrient management enhances vegetative growth, nutrient uptake, and soil fertility in rice systems. Poultry manure likely improved soil physical conditions, microbial activity, and nutrient release, thereby promoting vigorous tiller development. Similar findings were reported by Farooq et al. (2022), who noted that combining organic and inorganic nitrogen sources improves nitrogen synchronization and enhances rice growth under flooded conditions.

The significant increase in partial factor productivity (PFP) under phenology-based split and conventional split nitrogen applications confirms the importance of synchronizing fertilizer application with crop nutrient demand. Peng et al. (2006) similarly reported that site-specific and split nitrogen application strategies significantly improve nitrogen use efficiency and grain productivity in irrigated rice systems. Likewise, Liu et al. (2020) found that optimized nitrogen scheduling reduced nitrogen losses and improved nutrient uptake efficiency in rice production systems. The higher PFP values observed in the present study therefore suggest that split nitrogen application improved the efficiency with which applied nitrogen produced grain yield. However, agronomic efficiency (AE), physiological efficiency (PE), and recovery efficiency (RE) were not significantly affected by treatments. This result agrees partly with the findings of Sung et al. (2023), who observed that variations in NUE indices are sometimes inconsistent under controlled environmental conditions due to differences in nutrient uptake and internal nitrogen utilization.

Despite improvements in vegetative growth and nitrogen use efficiency, yield and yield-related parameters were not significantly affected by nitrogen management practices. This finding contrasts with several field-based studies that reported significant yield increases under improved nitrogen management. For example, Zhu et al. (2019) observed increased rice yield and NUE under side-deep fertilization and split nitrogen application. Similarly, Wang et al. (2022) reported that enhanced-efficiency fertilizers and precision nitrogen management significantly improved rice yield and grain quality. However, the lack of significant yield response in the present study may be attributed to the controlled screen house environment, restricted root volume under pot conditions, or relatively adequate baseline soil fertility. Wu et al. (2018) also reported that improvements in vegetative growth do not always translate directly into significant grain yield increases, especially under controlled conditions where environmental stress is minimized.

Biomass accumulation was significantly improved under poultry manure combined with reduced nitrogen fertilizer, which produced the highest whole plant wet weight, root wet weight, leaf dry weight, stem dry weight, and total dry weight. This finding supports the report of Chivenge et al. (2021), who concluded that integrated nutrient management enhances biomass production through improved soil nutrient availability and increased nutrient retention. Farooq et al. (2022) also observed that organic amendments improve root growth, microbial activity, and nutrient cycling, thereby promoting greater biomass accumulation in rice systems. The increased root biomass observed under poultry manure treatment in the present study may have enhanced nutrient and water uptake, contributing

to higher dry matter production. Similar observations were reported by Liu et al. (2020), who found that integrated nitrogen management improves assimilate production and dry matter accumulation in rice crops.

The relatively poor performance of foliar nano-urea in several growth and biomass parameters contrasts with some recent reports suggesting positive effects of nano-fertilizers on crop performance. However, the findings agree with the observations of Kumar et al. (2024), who emphasized that the effectiveness of nano-fertilizers depends strongly on environmental conditions, crop species, and application methods. Under flooded lowland conditions, foliar nano-urea alone may not have supplied sufficient nitrogen to sustain vigorous vegetative growth compared with soil-applied nitrogen sources.

A limitation of this study is the use of only three replications per treatment, which may have reduced the statistical power to detect true treatment differences. The limited number of replications increases the likelihood of Type II errors, where real differences are not identified as statistically significant. This is particularly relevant for the yield component traits and nitrogen use efficiency (NUE) indices that showed non-significant differences among treatments, as greater replication may have improved the precision of the estimates and enhanced the ability to detect subtle but biologically meaningful treatment effects. Future studies should consider increasing the number of replications to strengthen statistical robustness and improve confidence in treatment comparisons.

Overall, the findings of this study agree with previous research emphasizing the importance of integrated nutrient management and efficient fertilizer scheduling in rice production. The superior biomass accumulation under poultry manure combined with reduced mineral nitrogen and the improved PFP under split nitrogen application support the findings of Peng et al. (2006), Chivenge et al. (2021), and Wang et al. (2022), who all concluded that combining organic nutrient sources with improved nitrogen timing enhances nitrogen use efficiency and promotes sustainable rice production while minimizing environmental nitrogen losses.

Conclusions

Across the evaluated growth, yield, biomass, and nutrient use efficiency parameters, nitrogen management practices showed variable effects depending on the trait measured. Plant height was not significantly affected at early growth stages (2–12 WAT), but significant differences emerged at 14 WAT, with conventional split and slow-release nitrogen treatments producing the tallest plants, indicating improved nitrogen availability during later growth. Tiller production was significantly influenced during active vegetative stages (8–12 WAT), with poultry manure + reduced nitrogen consistently producing the highest number of tillers, suggesting superior enhancement of vegetative development compared with other treatments. In contrast, yield components including panicle length, number of panicles per plant, 1000-grain weight, grain yield per plant, and grains per panicle were not significantly affected by nitrogen management, although some treatments such as conventional split and foliar nano-urea showed relatively higher numerical values,

indicating broadly comparable reproductive performance across treatments. For nutrient use efficiency indices, nitrogen management significantly affected only partial factor productivity (PFP), with phenology-based split and conventional split applications recording the highest values, while agronomic efficiency, physiological efficiency, and recovery efficiency were not significantly influenced. Wet biomass accumulation showed significant responses in whole plant wet weight and root wet weight, with poultry manure + reduced nitrogen consistently producing the highest values, reflecting enhanced vegetative growth and root development, while leaf and stem wet weights were not significantly affected. Similarly, dry matter accumulation was significantly improved in leaf, stem, and total plant dry weight under poultry manure + reduced nitrogen, confirming its superior role in promoting overall biomass production. In general, while yield attributes remained largely unaffected, integrated organic–inorganic nitrogen management, particularly poultry manure combined with reduced nitrogen, demonstrated consistent superiority in enhancing vegetative growth and biomass accumulation, whereas split and phenology-based nitrogen applications were more effective in improving nitrogen use efficiency, particularly PFP.

Recommendation

Poultry manure combined with reduced nitrogen is recommended for enhancing vegetative growth and biomass production, while phenology-based and conventional split nitrogen application are recommended where the primary objective is improved partial factor productivity and efficient nitrogen management. Since grain yield and most yield components were not significantly affected, nitrogen management should focus on optimizing rather than maximizing nitrogen input, with emphasis on synchronizing nitrogen availability with crop demand and integrating organic and inorganic nutrient sources.

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