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Controlled-Release nitrogen enhances rice (*Oryza sativa* L.) productivity and profitability

El nitrógeno de liberación controlada mejora la productividad y la rentabilidad del arroz (*Oryza sativa* L.)

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ABSTRACT

Nitrogen losses associated with conventional fertilization reduce nitrogen use efficiency and limit productivity in irrigated rice systems. This study evaluated the effect of controlled-release urea with a urease inhibitor (NITROXTEND+S) on the yield of irrigated rice (*Oryza sativa* L.) in Huila, Colombia. The field trial (2 ha) was conducted using a randomized complete block design with four nitrogen (N) treatments: T1 (0%), T2 (50%), T3 (100%), and T4 (150%). Five fertilizer applications were performed in 2023 (March 22 and 29, and April 1, 15, and 25), following the agronomist's technical recommendations based on soil chemical analysis and weekly crop monitoring. Phenological variables and yield (using 50 × 50 cm measuring devices) were evaluated, and Shapiro-Wilk, ANOVA, and Fisher's LSD tests were applied. The yield of green paddy rice (mean ± SE) was: T1 = 5.86 ± 0.12, T2 = 7.19 ± 0.25, T3 = 9.48 ± 0.19, T4 = 7.91 ± 0.15 t ha^{-1}; T3 exceeded the national and departmental averages. It is concluded that inadequate doses (below or above the crop's nutritional requirements) reduce production, and that the optimal use of controlled-release nitrogen with a urease inhibitor improves productivity and nutrient use efficiency.

Keywords: cost-benefit ratio; fertility and nutrition; phenology; plant height; urea; urease inhibitor

RESUMEN

Las pérdidas de nitrógeno asociadas a la fertilización convencional reducen la eficiencia en el uso del nutriente y limitan la productividad de los sistemas arroceros bajo riego. Este estudio evaluó el efecto de la urea de liberación controlada con inhibidor de ureasa (NITROXTEND+S) sobre el rendimiento del arroz (*Oryza sativa* L.) bajo riego en Huila, Colombia. El ensayo de campo (2 ha) se diseñó en bloques completos al azar con cuatro tratamientos de N: T1 (0 %), T2 (50 %), T3 (100 %) y T4 (150 %). Se realizaron cinco fertilizaciones en 2023 (22/03, 29/03, 01/04, 15/04 y 25/04), siguiendo recomendaciones técnicas del agrónomo basadas en análisis químico de suelo y monitoreo semanal del cultivo. Se evaluaron variables fenológicas y rendimiento (aforadores 50×50 cm) y se aplicaron Shapiro–Wilk, ANOVA y LSD de Fisher. El rendimiento en arroz paddy verde (media ± EE) fue: T1 = 5,86 ± 0,12, T2 = 7,19 ± 0,25, T3 = 9,48 ± 0,19, T4 = 7,91 ± 0,15 t ha^{-1}; T3 superó los promedios nacionales y departamentales. Se concluye que dosis inadecuadas (por debajo o por encima de los requerimientos nutricionales del cultivo) reducen la producción, y que el uso óptimo de nitrógeno de liberación controlada con inhibidor de ureasa mejora la productividad y la eficiencia del uso del nutriente.

Palabras clave: relación costo-beneficio; fertilidad y nutrición; fenología; altura de planta; urea; inhibidor de ureasa

INTRODUCTION

Rice (*Oryza sativa* L.) is a short-cycle crop whose rapid turnover can reduce investment time and accelerate returns for producers (Sandhu *et al.,* 2021). In Colombia, the main rice-producing regions are Tolima, Huila, and the Eastern Plains; despite domestic production, national demand is not fully met, and the country imports rice from the United States, Ecuador, and Peru (Gallego López & Méndez Acevedo, 2023). Against this backdrop, improving fertilization strategies that increase yield without inflating costs or environmental burdens remains a priority.

Nitrogen (N) is the single most influential nutrient in rice performance: it drives vegetative vigor, tillering, leaf area expansion, spikelets per panicle, the proportion of filled spikelets, and grain protein content (Dobermann & Fairhurst, 2005). Efforts to optimize N management (dose, timing, and placement) are central to maximizing yield (Ju *et al.*, 2021). Locally, spectral monitoring of Fedearroz-67 under Tolima conditions showed N deficiency during early tillering and high N uptake at maximum tillering, flowering, and milky grain stage—evidence that rice demand for N peaks at specific phenophases (Polania Montiel, 2017). Complementarily, fieldwork in Peru identified 140 kg N ha^{-1} as an effective rate for direct-seeded irrigated rice at seeding densities of 60–80 kg ha^{-1}, linking agronomic practices to yield and economic outcomes (Flores Ponte, 2017).

Despite the central role of N, conventional fertilization in flooded rice often suffers from inefficiencies: more than half of the applied N can be lost from the system, generating environmental risks and economic losses (Geng *et al.*, 2015). Loss pathways include volatilization, leaching, nitrification–denitrification, and runoff, all of which attenuate crop response to N inputs (Qi *et al.*, 2020; David & Otsuka, 1994). Consequently, strategies to slow urea hydrolysis, reduce ammonia losses, and better align N availability with crop demand have been pursued (Bagheri Novair *et al.,* 2021; Mumtaz *et al.*, 2019).

Controlled-release nitrogen fertilizers (CRNF) address these limitations by embedding nutrients in coatings or matrices that regulate the rate and duration of nutrient delivery (Vejan *et al.*, 2021). Polymer-coated urea (one common CRNF) delays nutrient release and mitigates leaching risk, improving synchrony between soil N supply and plant demand (Lawrencia *et al.*, 2021). In rice systems, controlled-release urea (CRU) has increased NUE and grain yield while lowering ecological impacts on a life-cycle basis (Xu *et al.*, 2022). Multi-year trials have shown that CRU applied at 240–360 kg N ha^{-1} can raise yield by ~21–29% compared with conventional urea and improve late-season N availability as leaching declines (Zhang *et al.*, 2018). Moreover, combining CRNF with locally recommended urea (e.g., 60% CRNF + 40% urea) can enhance NUE and cost–benefit relative to single-source strategies (Lyu *et al.*, 2021).

While international evidence indicates agronomic and environmental advantages of CRU/CRNF, field-scale data that jointly quantify agronomic yield and techno-economic performance of controlled-release urea with a urease inhibitor under irrigated tropical conditions in Colombia are limited. In particular, comparative responses across sub-optimal, optimal, and excessive N rates (and their profitability implications) have not been clearly established in Huila's irrigated production context using the specific technology assessed in this study. To address this knowledge gap, this study evaluated the agronomic and economic effects of applying controlled-release urea with a urease inhibitor at 0%, 50%, 100%, and 150% of the recommended N rate in irrigated rice under field conditions in Huila, Colombia.

Applying controlled-release urea with a urease inhibitor at the optimal N rate will increase grain yield and profitability relative to insufficient (sub-optimal) or excessive

N rates by improving NUE and reducing volatilization/leaching losses. Urease catalyzes urea hydrolysis to ammonium and carbon dioxide in soil; rapid hydrolysis can elevate pH in the microsites and drive ammonia volatilization. Urease inhibitors such as *N-(n-butyl) thiophosphoric triamide* (NBPT) transiently block urease activity, slowing urea hydrolysis, reducing NH_3 losses, and allowing more urea to convert to plant-available forms in synchrony with crop demand. When coupled with controlled-release coatings, the technology further tempers N supply, collectively enhancing NUE and stabilizing yield response (Lawrencia *et al.,* 2021; Vejan *et al.,* 2021; Dobermann & Fairhurst, 2005). Building on these considerations, this study evaluated the effect of four fixed N levels delivered as controlled-release urea with a urease inhibitor (NITROXTEND+S) on irrigated rice yield, phenological traits (e.g., tillering, panicle formation, and plant height), and cost–benefit under field conditions in Huila, Colombia.

MATERIALS AND METHODS

The study was conducted at the Experimental Farm of the Universidad Surcolombiana, located at 2°57’N, 75°26’W (Palermo, Huila, Colombia). The net experimental area was 2 ha, divided into four plots of 0.5 ha each, excluding 1 m buffer zones (see Figure 1). The experiment was arranged in a randomized complete block design (RCBD) with one factor (nitrogen dose) at four levels: 0%, 50%, 100%, and 150%. Blocks were established to control variability in soil microtopography and irrigation distribution. The experiment was conducted during a single crop cycle from March to June 2023 under irrigated conditions.

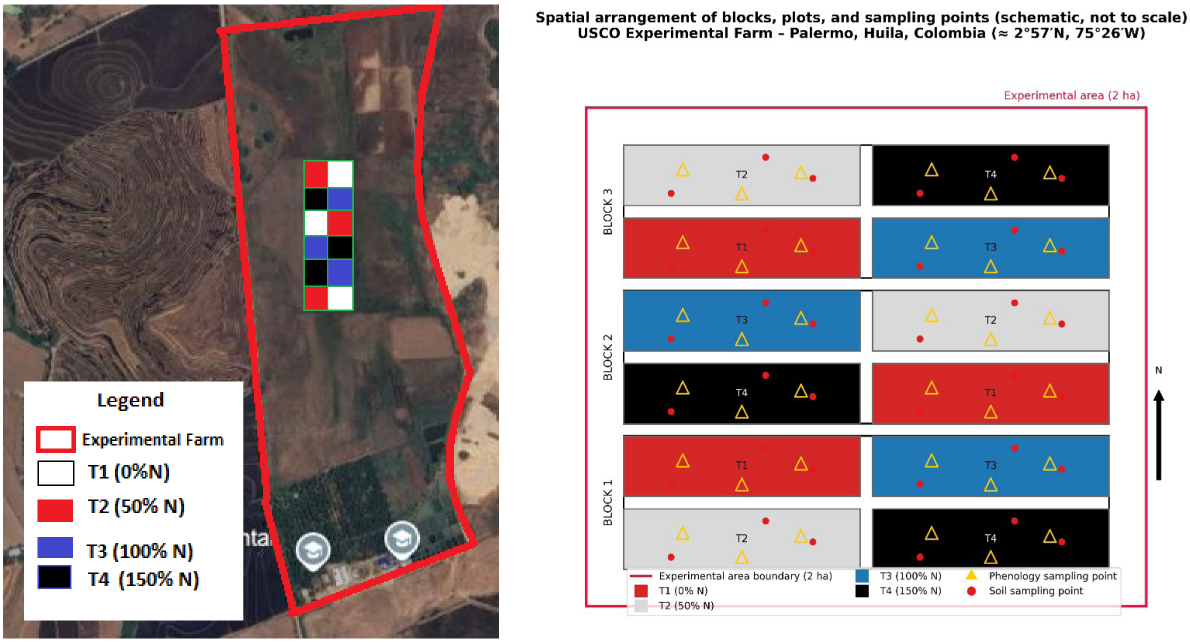


Figure 1. *Satellite image of the USCO experimental farm and delimitation of the study plot. Spatial arrangement of blocks, plots, and sampling points.*

Soil sampling was conducted before soil preparation, with three samples collected for each plot, and there were 4 plots per block. The locations of the sampling points, as well as soil and phenological monitoring of the crop, were determined using the conditioned Latin hypercube (cHL) method, implemented with an algorithm in RStudio® and with area maps processed in QGIS®. cHL ensures a random distribution of the sampling points. To avoid edge effects in plot delineation, buffers of one meter were created.

Soil sampling followed the protocol established by the Instituto Geográfico Agustín Codazzi (IGAC). The samples were taken to the Soil Laboratory LABGAA of the Universidad Surcolombiana. The initial soil chemical properties are summarized in Table 1, including pH, organic carbon, available phosphorus, exchangeable bases, micronutrients, and cation exchange capacity.

Table 1. *Initial Soil Chemical Properties of the Experimental Site.*

Parameter	Unit	Value	Method
pH	-	5.6	NTC 5264
Organic carbon	%	1.34	NTC 5403 (modified)
Available phosphorus	mg/kg	12.5	NTC 5350 (modified)
Potassium (K)	cmol/kg	0.28	NTC 5349 (modified)
Calcium (Ca)	cmol/kg	4.2	NTC 5349 (modified)
Magnesium (Mg)	cmol/kg	1.8	NTC 5349 (modified)
Sulfur (S)	mg/kg	18.0	NTC 5402 (modified)
Cation exchange capacity	cmol/kg	12.6	NTC 5268 (modified)
Electrical conductivity	dS/m	0.21	Laboratory method
Boron (B)	mg/kg	0.35	Hot water method
Iron (Fe)	mg/kg	45.0	NTC 5526 (modified)
Manganese (Mn)	mg/kg	12.0	NTC 5526 (modified)
Zinc (Zn)	mg/kg	1.2	NTC 5526 (modified)
Copper (Cu)	mg/kg	0.8	NTC 5526 (modified)

For soil preparation, primary tillage machinery (harrow) was used, where three passes were made, and the soil was adapted through micro-levelling with Land Plane and ridging with Taipa. The type of irrigation used was slope irrigation.

The FEDEARROZ seed variety (FL FEDEARROZ 2020) was used at a sowing density of 150 kg/ha with pre-fertilization with diammonium phosphate (DAP). A 17-row Montana seeder was used.

The portfolio of products used for fertilization in each treatment was established by the agricultural engineer advisor to the project, according to the results of the preliminary soil characterization and the condition of the crop. The 100% nitrogen rate was established, from which the doses of the different treatments were made. The controlled-release urea used to fertilize the crop was NITROXTEND+S, which is a nitrogen fertilizer coated with N-(n-butyl) thiophosphoric triamide, an inhibitor of the urease enzyme. This technology avoids nitrogen losses by volatilization, thereby increasing the nutrient efficiency in the crop. Table 2 summarizes the fertilization plan implemented for each nitrogen treatment during the single crop cycle (March–June 2023). The schedule includes the five application dates, the products used, and the corresponding doses per hectare. All treatments were based on soil analysis and agronomic recommendations, with controlled-release urea (NITROXTEND+S) as the main nitrogen source.

Table 2. *Fertilization schedule and nitrogen doses applied per treatment during the crop cycle.*

Application No.	Application date	Product	Dose for T3 - 100% (0.5 ha)
1st	22/03/2023	N	37.5 kg
1st	22/03/2023	N - S	37.5 kg
1st	22/03/2023	K - Cl	25 kg
1st	22/03/2023	B - Zn	5 kg
2nd	29/03/2023	N	50 kg
2nd	29/03/2023	N - S	25 kg
2nd	29/03/2023	K - Cl	25 kg
2nd	29/03/2023	Fe - S	5 kg
2nd	29/03/2023	Mn - S	2.5 kg
3rd	01/04/2023	N	50 kg
3rd	01/04/2023	Mg - S - Ca	50 kg
3rd	01/04/2023	K - Cl	25 kg
4th	15/04/2023	N	50 kg
4th	15/04/2023	Mg - S - Ca	37.5 kg
4th	15/04/2023	K - Cl	25 kg
5th	25/04/2023	N	37.5 kg
5th	25/04/2023	K - Cl	12.5 kg

During the crop cycle, different measurements were taken according to the progress of the phenological stage, using “50cm × 50cm” quadrats, which were placed on the ground with a flag for their location and prior identification.

The first measurement was conducted 10 days after reaching 100% germination, when the initial plant population was counted to verify whether the established planting density had been achieved.

Due to the intense rainfall in the days after sowing, germination was slow, causing 100% seed emergence to take longer to occur. This occurred 20 days after sowing, taking 10 days longer than established in the seed characteristics. The Shapiro-Wilk test was performed on the initial population count to revise the normality of the data, and an analysis of variance (ANOVA) was used to evaluate statistically significant differences between treatments.

At tillering (30 DAG), maximum tillering and panicle initiation (38 DAG), maximum fruit set (75 DAG), and flowering (80 DAG), the number of tillers was recorded, and the height of three plants within each quadrat was measured.

Harvesting was carried out manually at 90 DAG for treatments T1 and T2, and at 100 DAG for treatments T3 and T4. All plants within each quadrat were harvested to determine the number of panicles, plant height, total grain weight, the percentage of unfilled grains, the number of grains per quadrat, and the 1,000-grain weight.

Using the data collected on the number of tillers at each phenological stage, the Shapiro-Wilk test, box-and-whisker plots, analysis of variance (ANOVA), and Fisher’s LSD test were performed to determine whether statistically significant differences existed between the different treatments. The experiment was conducted under uniform field conditions using a randomized complete block design to minimize variability among plots. Given the controlled environment and balanced replication, variance homogeneity was assumed for ANOVA, as commonly accepted in agronomic field trials. Additionally, orthogonal polynomial contrasts (linear, quadratic, and cubic) were performed on projected yield per hectare within the one-way ANOVA to evaluate ordered dose trends, using equal replication per treatment and the MSW from the ANOVA.

RESULTS

Figure 2 summarizes the distribution of the initial plant population (plants m^{-2}) across nitrogen treatments using box-and-whisker plots. Normality was confirmed for all groups by the Shapiro–Wilk test (p > 0.20), and one-way ANOVA detected no significant differences among treatments ($F_{3,32}$ = 0.225, p = 0.878), indicating that the experimental plots started with comparable plant densities. Descriptive statistics for each treatment, including means, medians, quartiles, and normality test results are provided in Supplementary Table S2. The mean (median) plant counts were T1 = 268.0 (272), T2 = 260.9 (260), T3 = 271.1 (280), and T4 = 269.3 (260) plants m^{-2}, with interquartile ranges between 36 and 48 plants m^{-2}. These results confirm that the recommended target density (≈250–300 plants m^{-2}) was achieved uniformly, ensuring that subsequent phenological and yield differences can be attributed to nitrogen treatments rather than initial stand variation.

Figure 2. *Box of whiskers initial population*

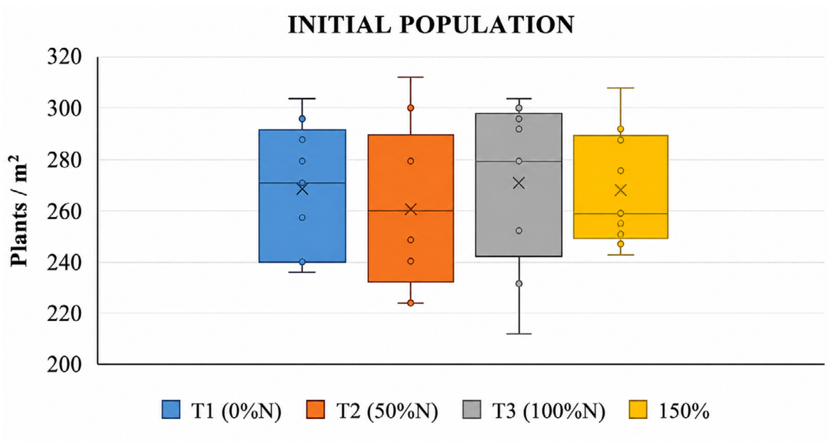
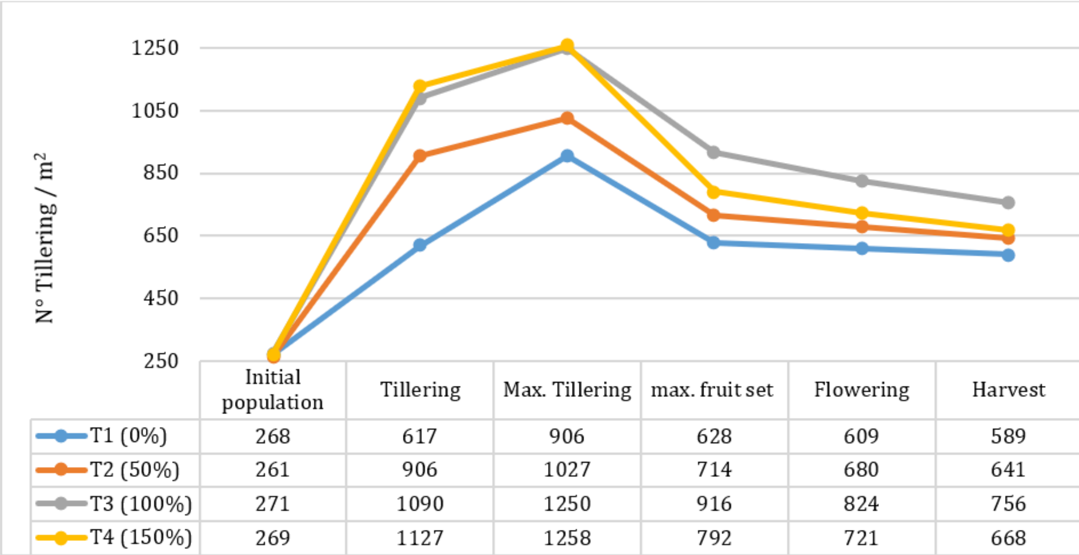


Figure 3 depicts the temporal dynamics of tiller density across phenological stages (tillering, maximum tillering, maximum fruit set, flowering, and harvest) under four nitrogen rates (0%, 50%, 100%, 150%). For each stage, normality was supported by Shapiro–Wilk tests (p > 0.05), and one-way ANOVA identified significant treatment effects (Tillering: $F_{3,32}$ = 35.37, p = 2.82×10^{-10}; Maximum tillering: $F_{3,32}$ = 19.68, p = 2.05×10^{-7}; Maximum fruit set: $F_{3,32}$ = 74.79, p = 1.50×10^{-14}; Flowering: $F_{3.32}$ = 38.16, p = 1.11×10^{-10}; Harvest: $F_{3,32}$ = 17.06, p = 8.47×10^{-7}). Across stages, T3 (100% N) consistently achieved the highest means with relatively small dispersion (e.g., at maximum fruit set, mean = 916 plants m^{-2}, median = 920, SE ≈ 8.38), while T1 (0% N) exhibited the lowest counts and broader variability (e.g., mean = 552.9, median = 532, SE ≈ 25.73 at maximum fruit set). T4 (150% N) often approached T3 during vegetative expansion (e.g., maximum tillering mean = 1257.8, median = 1232) but tended to decline relative to T3 towards flowering and harvest, consistent with growth imbalances under excessive N. Complete descriptive statistics and normality test results for all stages and treatments are provided in Supplementary Table 3.



Note: Matching letters indicate no significant difference among treatments within the same stage; different letters denote statistically significant differences according to Fisher's LSD test ($p < 0.05$).

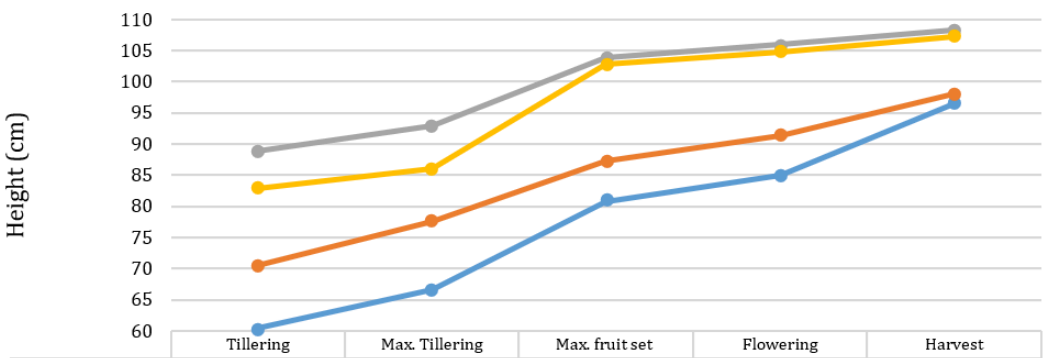
Figure 3. *Tiller density across five phenological stages*

Table 3. *Consolidated descriptive statistics, normality tests, and ANOVA results for tiller density across phenological stages and nitrogen treatments.*

Stage	Treatment	n	Mean	Median	SD	SE	Q1	Q3	IQR	Min	Max	Shapiro-Wilk W	Shapiro-Wilk *p*-value	ANOVA F (stage)	ANOVA p (stage)
Tillering	T1 (0% N)	9	616.89	652	107.27	35.76	548	680	132	432	772	0.94	0.55	35.37	2.82E-10
Tillering	T2 (50% N)	9	905.78	904	112.04	37.35	840	952	112	716	1100	0.99	0.99		
Tillering	T3 (100% N)	9	1089.78	1096	104.12	34.71	1032	1164	132	892	1248	0.98	0.95		
Tillering	T4 (150% N)	9	1126.67	1168	142.53	47.51	1000	1204	204	908	1312	0.94	0.55		
MaxTillering	T1 (0% N)	9	905.78	904	112.04	37.35	840	952	112	716	1100	0.99	0.99	19.68	2.05E-07
MaxTillering	T2 (50% N)	9	1026.67	1060	114.84	38.28	984	1060	76	856	1204	0.93	0.48		
MaxTillering	T3 (100% N)	9	1249.78	1268	117.51	39.17	1212	1320	108	1036	1388	0.93	0.49		
MaxTillering	T4 (150% N)	9	1257.78	1232	123.84	41.28	1172	1360	188	1104	1464	0.94	0.55		
MaxFruitSet	T1 (0% N)	9	552.89	532	77.20	25.73	512	616	104	440	668	0.95	0.73	74.79	1.50E-14
MaxFruitSet	T2 (50% N)	9	680.89	660	50.59	16.86	640	732	92	612	744	0.87	0.13		
MaxFruitSet	T3 (100% N)	9	916.00	920	25.14	8.38	904	928	24	880	960	0.98	0.94		
MaxFruitSet	T4 (150% N)	9	792.44	800	49.25	16.42	744	828	84	720	860	0.94	0.62		
Flowering	T1 (0% N)	9	609.33	612	46.39	15.46	600	628	28	532	684	0.96	0.84	38.16	1.11E-10
Flowering	T2 (50% N)	9	679.56	688	49.29	16.43	640	712	72	616	760	0.95	0.71		
Flowering	T3 (100% N)	9	824.44	832	24.61	8.20	804	840	36	792	856	0.90	0.25		
Flowering	T4 (150% N)	9	720.89	740	49.43	16.48	688	760	72	640	776	0.91	0.31		
Harvest	T1 (0% N)	9	588.89	600	44.58	14.86	556	624	68	520	648	0.95	0.68	17.06	8.47E-07
Harvest	T2 (50% N)	9	640.89	640	48.36	16.12	608	680	72	568	724	0.98	0.98		
Harvest	T3 (100% N)	9	754.44	776	51.98	17.33	704	796	92	670	808	0.87	0.11		
Harvest	T4 (150% N)	9	668.00	692	55.46	18.49	616	712	96	592	728	0.87	0.11		

Beyond the statistical confirmation of treatment effects, Figure 3 shows distinct physiological patterns across stages. Nitrogen supply strongly influenced the trajectory of tiller development: T3 (100% N) maintained a balanced, sustained increase, peaking at maximum tillering and preserving structural integrity through flowering and harvest. In contrast, T4 (150% N) exhibited an early surge in vegetative growth, surpassing T3 at maximum tillering, but this advantage diminished later, likely because excessive nitrogen promotes lush foliage and weaker stems, which predispose plants to lodging and reduced panicle formation. T1 (0% N) accelerated its phenological cycle under nutritional stress, resulting in premature senescence and the lowest tiller counts at reproductive stages. T2 (50% N) offered intermediate performance, suggesting partial mitigation of stress without achieving optimal vigor. These trends underscore the importance of synchronizing nitrogen availability with crop demand to avoid both deficiency and excess, which compromise yield stability and resource efficiency.

Figure 4 illustrates the progression of plant height across five phenological stages under four nitrogen rates (0%, 50%, 100%, 150%). Heights increased steadily from tillering to harvest in all treatments, with T3 (100% N) consistently achieving the greatest values (e.g., 108 cm at harvest), confirming its role in promoting vigorous and sustained growth. T4 (150% N) showed similar performance during vegetative stages but did not surpass T3 at reproductive stages, suggesting that excessive nitrogen favors early elongation without proportional gains in final height. In contrast, T1 (0% N) and T2 (50% N) exhibited shorter plants throughout the growing period, reflecting nutritional stress and accelerated phenological progression. ANOVA confirmed significant differences among treatments at all stages (F = 31.26 to 676.13, $p < 0.001$), and normality was supported by Shapiro–Wilk tests for most groups. Complete raw data, descriptive statistics, and ANOVA results are provided in Table 4. At the end of the phenological cycle, all four treatments comply with the plant characteristics established in the seed specifications, which indicate an average height of 90 to 100 cm (Fedearroz-FNA, 2014).



	Tillering	Max. Tillering	Max. fruit set	Flowering	Harvest
T1 (0%N)	60	67	81	85	96
T2 (50%N)	70	78	87	91	98
T3 (100%N)	89	93	104	106	108
T4 (150%N)	83	86	103	105	107

Figure 4. *Plant height across five phenological stages. Matching letters indicate no significant difference within a stage (Fisher's LSD, p < 0.05).*

Table 4. *Raw height measurements and consolidated descriptive statistics, normality tests, and ANOVA results across phenological stages and nitrogen treatments.*

Stage	Treatment	n	Mean	Median	SD	SE	Q1	Q3	IQR	Min	Max	Shapiro-Wilk W	Shapiro-Wilk *p*-value	Abs. diff	F	*p*-value
Tillering	T1 (0% N)	9	60.33	62	9.04	3.01	52	63	11	47	74	0.93	0.48	0.04	49.81	3.70E-12
Tillering	T2 (50% N)	9	70.44	70	1.81	0.60	70	72	2	67	73	0.95	0.71	0.04		
Tillering	T3 (100% N)	9	89.00	87	5.70	1.90	85	92	7	84	99	0.83	0.05	0.11		
Tillering	T4 (150% N)	9	82.78	83	0.83	0.28	82	83	1	82	84	0.81	0.03	0.15		
MaxTillering	T1 (0% N)	9	66.56	69	7.91	2.64	62	70	8	54	80	0.95	0.70	0.00	31.26	1.24E-09
MaxTillering	T2 (50% N)	9	77.56	77	3.94	1.31	75	80	5	71	85	0.96	0.85	0.04		
MaxTillering	T3 (100% N)	9	93.00	90	7.07	2.36	88	97	9	87	108	0.84	0.06	0.04		
MaxTillering	T4 (150% N)	9	87.44	87	5.27	1.76	83	88	5	82	96	0.84	0.05	1.37		
MaxFruitSet	T1 (0% N)	9	80.78	80	1.86	0.62	79	82	3	79	84	0.88	0.16	0.04	389.62	2.95E-25
MaxFruitSet	T2 (50% N)	9	87.22	87	2.49	0.83	86	89	3	84	91	0.95	0.66	0.03		
MaxFruitSet	T3 (100% N)	9	104.11	104	1.54	0.51	103	105	2	102	106	0.91	0.31	0.30		
MaxFruitSet	T4 (150% N)	9	102.67	103	0.50	0.17	102	103	1	102	103	0.62	0.00	0.11		
Flowering	T1 (0% N)	9	84.89	85	1.27	0.42	84	86	2	83	87	0.95	0.66	0.04	676.13	5.25E-29
Flowering	T2 (50% N)	9	91.00	91	0.87	0.29	90	92	2	90	92	0.82	0.04	0.37		
Flowering	T3 (100% N)	9	106.22	106	1.64	0.55	106	107	1	104	109	0.91	0.34	0.30		
Flowering	T4 (150% N)	9	105.11	105	0.93	0.31	105	106	1	103	106	0.76	0.01	0.30		
Harvest	T1 (0% N)	9	96.22	97	2.44	0.81	94	98	4	93	99	0.84	0.06	0.19	79.95	5.92E-15
Harvest	T2 (50% N)	9	96.56	97	3.43	1.14	97	99	2	90	100	0.84	0.05	1.48		
Harvest	T3 (100% N)	9	108.11	108	1.17	0.39	108	109	1	106	110	0.94	0.59	0.11		
Harvest	T4 (150% N)	9	107.33	107	0.50	0.17	107	108	1	107	108	0.62	0.00	0.04		

Statistically significant differences were found in all treatments at the tillering and maximum tillering stages. In the maximum tillering, flowering, and harvest stages, the ANOVA analysis of variance showed that there was a significant difference in at least one of the treatments, and with Fisher's test, it was determined that the treatments T3(100%N) and T4(150%N) do not have significant differences.

Figure 5 compares the projected yield per hectare across nitrogen treatments using nine sampling frames per plot. Average yields (mean ± SE) were: T1 = 5.8569 ± 0.1188, T2 = 7.1869 ± 0.2467, T3 = 9.4781 ± 0.1904, and T4 = 7.9144 ± 0.1538 t ha^{-1}, with T3 (100% N) outperforming all other treatments. Shapiro–Wilk tests supported normality for each group and one-way ANOVA confirmed significant treatment effects ($F_{3,32}$ = 67.558, p = 6.16×10^{-14}). Fisher's LSD (0.529 t ha^{-1}) indicated that all pairwise differences among treatment means were significant, including the decline from T3 to T4, which suggests diminishing returns under excessive nitrogen. Consolidated raw data, summary statistics, ANOVA, and LSD results are provided in Table 5.

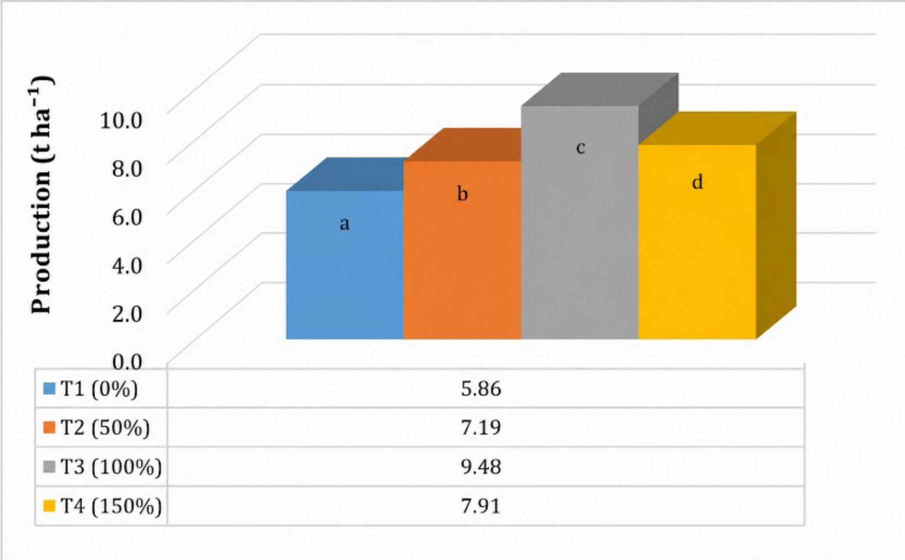


Figure 5. *Projected yield per hectare under four nitrogen rates. Bars represent treatment means. Different letters denote significant differences among treatments according to Fisher's LSD at α = 0.05.*

Polynomial contrasts across nitrogen rates (0%, 50%, 100%, and 150%) revealed a significant linear trend ($F_{1.32}$=107.45, p = 9.34 × 10^{-12}), a significant quadratic trend ($F_{1.32}$=62.80, p = 4.81 × 10^{-9}), and a significant cubic component ($F_{1.32}$=34.79, p = 1.46 × 10^{-6}). The negative sign of the quadratic component indicates a concave response—yield increases up to the recommended dose (100% N) and declines at 150% N, consistent with diminishing returns under excessive nitrogen. These contrasts were computed using the treatment means and the within-group mean square (MSW=0.30) reported in Table 5.

Table 5. *Raw harvest data and consolidated descriptive statistics, normality tests, ANOVA, and Fisher's LSD results for projected yield under different nitrogen treatments.*

Treatment	n	Mean	Median	SD	SE	Min	Max	Shapiro-Wilk W	Shapiro-Wilk p	ANOVA F	ANOVA *p*	MSW	t_crit (0.05)	LSD (t/ha)
T1 (0% N)	9	5.86	5.87	0.36	0.12	5.24	6.49	0.97	0.87	67.56	6.16E-14	0.30	2.04	0.53
T2 (50% N)	9	7.19	6.92	0.74	0.25	6.45	8.55	0.90	0.23					
T3 (100% N)	9	9.48	9.27	0.57	0.19	8.85	10.59	0.92	0.35					
T4 (150% N)	9	7.91	8.09	0.46	0.15	7.20	8.51	0.93	0.51					

Figure 6 summarizes the economic performance of each nitrogen treatment, including total production costs, gross income, and net profit per hectare. The optimal rate (T3, 100% N) achieved the highest profit (≈6.98 million COP) with moderate costs, confirming its superior cost–benefit ratio. In contrast, T4 (150% N) incurred the greatest investment (≈9.32 million COP) but generated only ≈3.66 million COP in profit, illustrating diminishing economic returns under excessive nitrogen. T1 (0% N) and T2 (50% N) showed lower profits (≈3.16 and 4.28 million COP, respectively), yet T2 offered a reasonable balance between cost and yield. These results highlight that profitability does not increase linearly with nitrogen input; beyond the recommended dose, additional costs outweigh marginal yield gains.

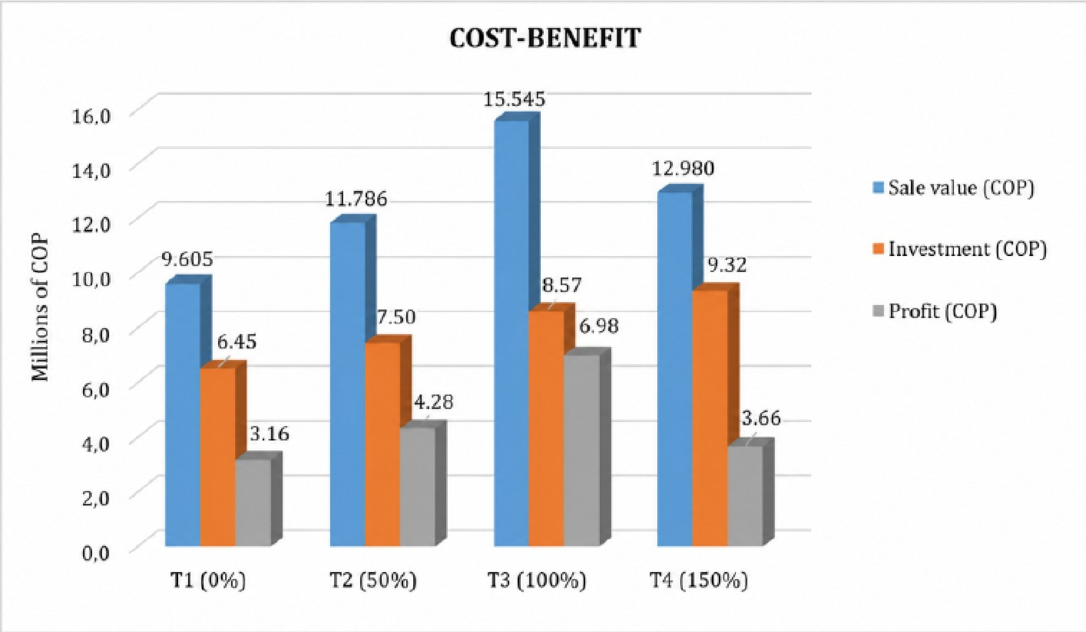


Figure 6. *Cost-benefit ratio of cultivation*

DISCUSSION

No significant differences were observed in the initial plant population among treatments; the average value of the initial population of each treatment was used, verifying that the values are within the range established and mentioned by Fedearroz, for an optimum yield with sowing densities of 120 kg/ha, between 265 and 286 plants per m^2 should be established (Guzmán *et al*., 2018). In this way, it is statistically proven that the proposed sowing density is guaranteed.

Tillering in rice cultivation is conditioned by the vegetative phase of the crop: germination (initial population), tillering, and maximum tillering. The number of tillers per plant determines the number of panicles per unit area (Garcés Varón & Medina Rubio, 2018). Each of the nutrients plays a specific role in plant metabolism. None of them can be replaced by another. Therefore, even if plants have adequate amounts of all other nutrients, a deficiency in the quantity or proportion of a single nutrient will limit crop growth and yield. This principle is known as the law of the minimum (Zabel *et al*., 2025).

At the stage of maximum tillering, treatments T1 and T2 had an advance of 10 days in the phenological cycle. This was due to the nutritional stress to which the crop was subjected. The lack of an essential nutrient, such as nitrogen, leads to the inability of the plants to create cells and generate energy, which eventually makes them vulnerable to premature senescence. During the flowering and harvesting stages, T4 exhibited a greater decrease in panicle, which is due the fact that excess of nitrogen in the rice crop can have several negative effects. Excess nitrogen increases the tendency to lodging (plant tipping), and a shortage causes a decrease in the number of tillers per plant, the number of spikelets per panicle, and the number of well-developed grains, leading in both cases to a lower yield (Dobermann & Fairhurst, 2005; Rodríguez Pérez, 2014; Lawrencia *et al*., 2021; Mula, 2026). Plants with an excess of nitrogen will become more susceptible to environmental variations, such as humidity and temperature, which increase their susceptibility to diseases and may reduce plant survival (Mula, 2026). It is also worth mentioning that yields will be lower, and the quality of the products will decrease considerably.

In the evaluation of plant height at the maximum tillering, flowering, and harvest stages, the analysis of variance (ANOVA) showed that there was a significant difference in at least one of the treatments. Fisher's test indicated that treatments T3(100%N) and T4(150%N) did not differ significantly. This is because nitrogen (N) is directly related to plant growth; N promotes rapid growth and increase in plant size, number of tillers and leaf size (Dobermann & Fairhurst, 2005). For this reason, treatments T1 (0%N) and T2 (50%N) exhibited the lowest plant heights.

In a visual analysis of the crop, treatments containing less nitrogen, T1 (0%N) and T2 (50%N), exhibited a yellowish colour, and their heights were lower than those containing more nitrogen. In treatments T3 (100%N) and T4 (150%N), plants exhibited greater vigor, with larger leaves and a more intense green color. However, in treatment T4 (150%N), there was a greater presence of weeds. The effects of nitrogen deficiency are manifested by chlorosis, i.e., a yellowing of the leaves. This appears first on the older leaves and, as it increases, affects the younger ones, as the plants can mobilize the nitrogen in the older leaves to the younger ones and to the growing points. In cases of extreme deficiencies, there can be growth arrest and leaf drop, and when plants have excess nitrogen, they show exaggerated growth as there is greater cell multiplication, so the number of shoots increases (Mula, 2026).

The national survey of mechanized rice (ENAM) for the first semester of 2023 mentions that the national average of rice was 6,338 tn/ha, and for the department of Huila, it was 7.29 tn/ha (DANE, 2023). The use of controlled-release urea as a source of nitrogen for rice cultivation reduces environmental pollution and allows greater efficiency in the use of nitrogen, as can be seen in Figure 5. Treatments T2, T3, and T4 showed yields per hectare above the national and departmental average, which are developed with traditional nitrogen sources, but T3 was the highest yielding and the best option for rice growers in the region to implement.

According to Dorado Urbano (2023), the average cost of one hectare of irrigated rice in the central region of Colombia in 2021 was COP 8'042.965. With an average yield of 7.46 t ha^{-1} over a crop cycle of approximately four months, the average gross income was COP 9,150,034 ha^{-1}, resulting in a net profit of COP 1,107,070 and a cost–benefit ratio of 1.13; however, the cost of the evaluated treatments did not consider items such as the lease of the lot. Treatments T3 and T4 registered investment values of 8'569,059.00 COP/ha and 9'322,209.00 COP/ha, respectively. They have a difference of 753,150.00 COP/ha in investment costs, T3 being the one with the lower investment cost among the two and the higher profit generated compared to the other treatments. Treatments T1 and T4 present similar profits, but the investment made for T4 is higher than the other treatments. Treatment T2 presents an investment cost per hectare below the average established by Dorado Urbano (2023) and mentioned above, with a production per hectare above the average, a model that can benefit rice growers by decreasing investment costs. The treatment that generated the highest profit for investment cost and sales value was T3.

CONCLUSIONS

The effect of controlled-release nitrogen on the yield of the rice crop (*Oryza sativa* L.) is determined by the amount of nitrogen supplied to the crop. Treatment T3 produced the highest yield, reaching 9.48 t ha^{-1}. The effect of applying the controlled-release nitrogen needed for the (T3) plant and not applying (T1) nitrogen has an economic impact on the farmer because there is a difference of approximately 3.62 tn/ha, due to the fact of guaranteeing the nitrogen needs of the plant. However, an excess (T4) can reduce the crop yield to approximately 1.57 tn/ha, affecting production as much as if only half of the nitrogen necessary for the plant (T2) were applied, which reduces it by approximately 2.29 tn/ha, generating economic losses and environmental pollution.

An excess amount of available nitrogen in the rice crop, as with T4 (150%N), reduced the number of tillers, causing excessive growth with weak stems and larger leaves, which disturbs the balance of the plant and may affect its ability to produce a healthy crop and reduce crop yields.

Nitrogen availability also affected the phenological cycle. Although all treatments reached complete emergence simultaneously, T1 (0% N) and T2 (50% N) exhibited accelerated phenological development compared with T3 (100% N) and T4 (150% N), likely as a result of nitrogen deficiency-induced nutritional stress.

AUTHOR CONTRIBUTIONS

Conceptualization, D.C.P.M., and J.G.A.M.; Methodology, J.C.A.V., D.C.P.M., and J.G.A.M.; Validation, J.G.A.M.; Formal Analysis, J.C.A.V., D.C.P.M., and J.G.A.M.; Investigation, J.C.A.V.; Resources, D.C.P.M., and J.G.A.M.; Data Curation, J.C.A.V.; Writing—Original Draft Preparation, J.C.A.V.; Writing—Review & Editing, D.C.P.M., and J.G.A.M.; Visualization, J.C.A.V.; Supervision, D.C.P.M., and J.G.A.M.; Project Administration, D.C.P.M., and J.G.A.M.; Funding Acquisition, D.C.P.M., and J.G.A.M.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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