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RESEARCH ARTICLE

Impact of neem-coated urea and nano urea on rice under Tamirabarani river basin

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Abstract

This study examined to evaluate the nitrogen use efficiency (NUE) of neem-coated urea (NCU), nano urea (NU) and productivity of two widely grown rice varieties, ASD16 and ADT46 around Tamirabarani River basin. Treatments included varying foliar dosages of NCU, NU, the recommended dose of fertilizers (RDF) and control. Results showed RDF significantly outperformed all treatments in quantitative parameters (plant height, tiller density, grain yield, straw yield) and qualitative parameters (chlorophyll content, leaf area index), followed by NCU, NU and the control. The balanced nutrient profile of RDF and soil-based application maximized uptake and plant growth, unlike the nitrogen-limited and foliar-dependent NCU and NU. Notably, NCU's higher nitrogen content (46 %) and slow-release properties via neem coating enhanced absorption compared to NU's lower nitrogen (4 %) and reliance on foliar uptake, which likely faced inefficiencies due to leaf surface limitations and environmental factors like humidity. These findings position RDF as the most effective option for optimizing rice productivity in this region, highlighting the critical role of comprehensive nutrient delivery and efficient absorption mechanisms.

Keywords: grain yield; nano urea; neem-coated urea; nitrogen use efficiency; rice

Introduction

Rice is undeniably one of the most significant staple food crops cultivated around the globe, playing an absolutely vital role in feeding an immense portion of the world's population, particularly in Asian countries (1). Among the nations worldwide, India proudly holds the prestigious position as the second largest producer of rice, just following China, which tops the global list in terms of rice production volume (2). The state of Tamil Nadu demonstrates remarkable prominence in rice cultivation, with this essential and life-sustaining grain accounting for approximately 60 % of the total net cultivated area in the region (3). However, much like other prominent rice basins scattered throughout the world, the Tamirabarani River basin is currently confronted with numerous and serious challenges that pose a significant threat to the sustainability of its rice ecosystem (4). The region is grappling with a severe shortage of surface irrigation resources, a pressing concern that is primarily attributed to the declining flows and reduced availability of water from the river itself (5). This decline has raised alarms about the potential impact on agricultural productivity (6). Furthermore, many farmers working within this basin are not effectively implementing *in situ* water conservation methods, leading to a rapid and concerning rate of groundwater withdrawal, which is unsustainable and poses further risks for long-term agricultural viability (7). A particularly troubling issue that exacerbates the situation is the indiscriminate and excessive application of chemical fertilizers, notably urea, which requires focused and immediate attention within this river basin as it significantly contributes to the pollution of local surface water bodies and negatively affects the ecosystem (8). The region's loose topography further complicates these environmental challenges, as it renders rice fields especially vulnerable to runoff, which unfortunately facilitates the quick transport of fertilizers directly into the Tamirabarani river (9). Fertilizer runoff and environmental pollution pose significant challenges to sustainable rice cultivation, particularly in regions like the Tamirabarani River basin, where loose topography accelerates nutrient loss into waterways (10). While traditional fertilizers contribute to these issues, there is a pressing need for alternatives that enhance efficiency and reduce ecological harm. Recent innovations, such as nano coatings, have shown promise in improving fertilizer use efficiency and minimizing pollution, yet scientific data on the effectiveness of neem-coated urea (NCU) and nano urea (NU) in the context of Tamirabarani's rice ecosystem remain scarce (11). To effectively mitigate these daunting environmental challenges, it becomes crucial and imperative to upscale the site-specific integrated nutrient management technologies, such as NCU and NU, which are vital for sustaining the rice ecosystem effectively within the Tamirabarani River basin (12).

Although NU is becoming more and more popular as a possible substitute for traditional fertilizers, its effectiveness in producing rice is still debatable, especially in areas with limited water resources like the Tamirabarani River basin. Despite being marketed as having high nitrogen-use efficiency, NU frequently produces inconsistent yields in field settings because of uneven fertilizer distribution and quick volatilization losses in submerged rice soils (13). Furthermore, rainfed or water-stressed settings make it challenging to attain the ideal weather and precise timing needed for its foliar application (14). One traditional practice that stands out in Tamil Nadu and has been used for generations is the coating of urea with neem oil, an age-old agricultural method believed to significantly enhance NUE, thereby minimizing water body pollution caused by the overuse of chemical fertilizers (15). NCU provides a more dependable solution by combining natural nitrification inhibition with slow-release nitrogen, which lowers leaching and volatilization losses while guaranteeing extended nutrient availability. This nutrient loss not only threatens water quality but also reduces the efficiency of traditional fertilizers, necessitating the exploration of more sustainable alternatives (16). Additionally, NCU is often regarded as a viable and effective alternative to synthetic chemical inhibitors that are aimed at reducing nitrous oxide emissions, which is a significant concern in the broader context of environmental sustainability (17).

Recognizing this significant gap in knowledge, a carefully designed field experiment was strategically conducted at the Tamirabarani research farm during the year 2023, with the specific objective of thoroughly investigating and studying the impacts of NCU and NU on rice cultivation practices. The primary objective was to examine the effects of NCU and NU on various growth parameters, yield and nitrogen use efficiency (NUE) in rice cultivation.

Materials and Methods

Site description

A field experiment was carried out during *Rabi* season, 2023. In the southern agroclimatic zone of Tamil Nadu, at V. O. Chidambaranar (VOC) Agricultural College and Research Institute, Killikulam. During the cropping period, temperatures ranged from 28.6 °C to 35.8 °C (maximum) and 15.1 °C to 17.9 °C (minimum). The crop received a total rainfall of 127.8 mm. Maximum and minimum relative humidity in the study area ranged between 83.6 % to 89.7 % and 60.4 % to 80.4 % respectively. The average bright sunshine hours during the crop growing period varied between 5.1 hr day^{-1} to 11 hr day^{-1}. The experimental soil was sandy clay loam (clay, 28 %; silt, 15 %; sand, 25 % and fine sand 31 %) in texture with a pH of 7.27, exhibiting a slight salinity. The soil organic carbon content was 0.51 %. The initial available soil nutrient status was 210 kg N ha^{-1}, 182 kg P_2O_5 ha^{-1}, 196 kg K_2O ha^{-1} respectively.

Experimental design

The study was carried out using three replications utilizing a split-plot design (SPD). Two types of rice were grown in the main plots: ASD16 (V1) and ADT46 (V2). Nine different nutrient management treatments were included in the sub-plots: four concentrations of NU foliar application (1 %, 2 %, 3 % and 4 % designated as N1 to N4), three concentrations of NCU foliar application (0.25 %, 0.5 % and 1 % designated as N5 to N7), recommended fertilizer dose (N8) and control plot (N9) respectively. To assess the relative effectiveness of the foliar applications, a basal dose of 25 % nitrogen was applied to all treatments, with the exception of the control.

Crop cultivation

Transplantation was carried out using rice seedlings that were 21 days old. A basal dose of 120:40:40 kg ha^{-1} of N, P_2O_5 and K_2O was applied using urea, diammonium phosphate (DAP) and muriate of potash (MOP) respectively. Foliar applications of NCU and NU were made on the leaves at various critical stages, specifically 14 days after transplanting (DAT), active tillering, panicle initiation and heading stages (Fig. 1).

Assessment of growth and yield

Five plants from each treatment were randomly selected to evaluate various growth and yield parameters. This assessment included measuring plant height (cm) (18), SPAD (Soil and Plant Analysis

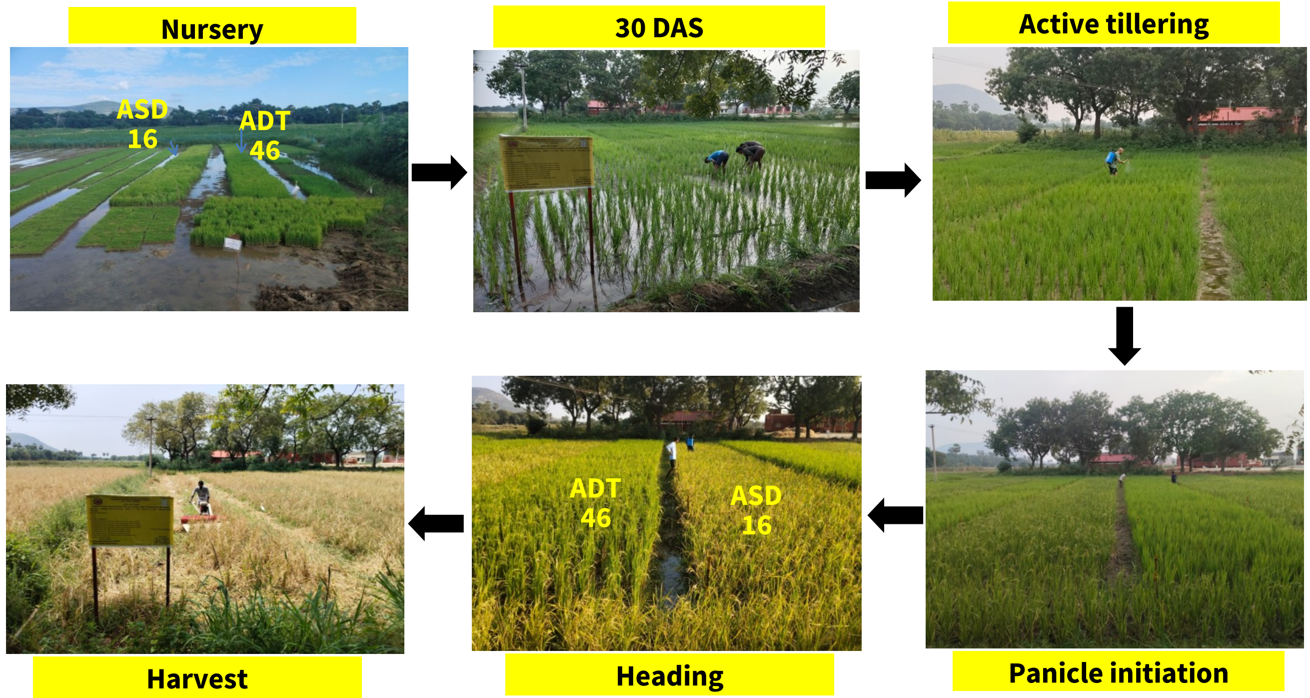

Fig. 1. Crop growth stages of ASD 16 and ADT 46 as influenced by the application of NU and NCU.

Development) meter readings (19), leaf area index (LAI; m^2 m^{-2}) (20), tiller density (no. m^{-2}) (21), panicle length (cm), number of filled grains $panicle^{-1}$, grain yield (kg ha^{-1}), straw yield (kg ha^{-1}) (22) and agronomic NUE (%) (23).

Statistical analysis

The experimental data were analysed using analysis of variance (ANOVA) in RStudio (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria). Standard error of mean (SEM) and least significant differences (LSD) at 5 % probability were calculated for multiple comparisons (24).

Plant height

The study indicated that NCU consistently performed better than NU formulations. It also showed that there were substantial differences in plant height between treatments. Among non-RDF (non-recommended dose of fertilizer) treatments, NCU at 0.5 % (N6) produced the tallest plants (137.55 cm), 25.2 cm (22.4 %) taller than the NU treatment (N4 at 4 %) (Table 1). The bioactive triterpenoids, particularly azadirachtin, present in the neem oil coating inhibit the urease enzyme and suppress the activity of *Nitrosomonas* bacteria, slowing the conversion of ammonium to nitrate (25). Additionally, this inhibition of nitrification keeps nitrogen in the plant-available ammonium form for two to three weeks, as opposed to seven to ten days for conventional urea. This dual-action mechanism of NCU is what causes this remarkable growth enhancement (26). The NCU-treated plants maintain 8 %-25 % higher chlorophyll content during critical growth periods. However, despite the fact that NU's smaller particle size (20 nm-50 nm) enhances foliar absorption through stomatal absorption, its uncontrolled release kinetics result in nutrient depletion (within 5-7 days), necessitating frequent reapplication (27, 28), . This is the reason why NCU performed better than even quadruple-strength NU (4 %) in this instance. The results proved that NCU enhanced plant height by 18 %-22 % more than NU. Additionally, they confirmed findings about the limitations of nutrient delivery using nanoparticles in field conditions.

Tiller density

Tiller production had even more significant treatment effects, with NCU at 0.5 % (N6) reaching 215.5 tillers m^{-2}, a 21.7 % increase above the maximal NU treatment (N4). This improved performance reveals NCU's capacity to sustain nitrogen availability throughout the critical tillering phase (20-40 days post-transplant). While NU concentrations fell below 10 ppm by day 10, NCU kept NH_4^+-N levels above the 25 ppm threshold for tiller initiation for 21 days after application. The range of 193-215 tillers/m^2 across NCU treatments versus 166-177 for NU is directly consistent with this. Such a continuous nitrogen supply is crucial since each tiller requires around 0.15 mg-0.20 mg of nitrogen per day during active growth (29). The recommended dose of fertilizer (RDF; 239 tillers m^{-2}), whose split-application schedule closely approaches the sustained release pattern of NCU, confirmed these trends. The varietal response clearly showed that ADT46 had a higher tillering capability under NCU (226.67 tillers m^{-2} at 1 %) than ASD16 (192.4). These findings of cultivar-specific reactions to enhanced-efficiency fertilizers, resulted due to genetic variations in NUE. These results demonstrate the advantage of NCU in synchronizing nitrogen release with the tiller growth window (35-55 DAS), an important factor that is overlooked by NU's rapid-release characteristics (30).

Soil and Plant Analysis Development (SPAD) meter readings

The study's SPAD meter data showed significant treatment effects and NCU consistently performed better than NU formulations (31). NCU at 0.5 % (N6) had peak mean SPAD values (39.12), 13.6 % higher than the best-performing NU treatment (N3: 36.28) (Table 2). This improvement results from NCU's enhanced nitrogen delivery system, which, because of the neem oil coating's ability to prevent nitrification, maintains optimal leaf nitrogen concentrations throughout the development cycle. The gradual release of nitrogen from NCU supports continuous chlorophyll synthesis and avoids boom-bust cycles that are common in classical and NU applications (12). These findings are in line with well-established physiological principles, which state that extended nitrogen availability improves chlorophyll concentration and stability, leading to more stable photosynthetic activity. The increased SPAD values under NCU treatment were especially beneficial to the reproductive period, when panicle development and grain filling depend on an adequate nitrogen supply (32). Higher SPAD responsiveness to NCU was shown by ADT 46, suggesting genetic variations in NUE that requires further investigation.

Leaf Area Index

Treatment effects on LAI validated NCU's superiority in canopy development and among non-RDF treatments, NCU at 0.5 % achieved the highest mean LAI (5.225 m^2 m^{-2}). This represents a 7.2 % improvement over the best NU treatment and a 14.5 % increase over control (Table 2). The enhanced LAI under NCU reflects its ability to maintain prolonged leaf expansion and tiller development during

Table 1. Plant height and tiller density of rice as influenced by the application of NU and NCU

Treatment		Plant height (cm)			Tiller density (No. s m^{-2})		
		ASD 16	ADT 46	Mean	ASD 16	ADT 46	Mean
N1 - NU @ 1 %		103.83	106.26	105.05	159.57	174.24	166.91
N2 - NU @ 2 %		108.06	109.06	108.56	163.68	179.47	171.58
N3 - NU @ 3 %		105.22	108.68	106.95	164.64	182.31	173.48
N4 - NU @ 4 %		106.29	109.4	107.85	168.72	185.42	177.07
N5 - NU @0.25 %		110.00	115.78	112.89	188	198.33	193.17
N6 - NU @ 0.5 %		115.57	121.54	118.55	212.67	212.33	212.5
N7 - NU @ 1 %		111.94	116.72	114.33	192.4	205.67	199.04
N8 - RDF		98.73	102.04	100.39	168	176.33	172.17
N9 - Absolute control (0 % N)		91.78	98.01	94.895	141.67	156.42	149.05
Mean		105.71	109.72		173.26	185.61	
	N		**V**		**V@N**		**N@V**
			Plant height				
SED	3.26		4.72		6.81		4.35
CD (0.05)	6.74		10.21		13.16		8.62
			Tiller density				
SED	4.05		6.52		11.12		10.47
CD (0.05)	8.31		13.17		24.43		21.31

Table 2. SPAD and LAI of rice as influenced by the application of NU and NCU

Treatment	SPAD			LAI ($m^2 m^{-2}$)		
	ASD 16	ADT 46	Mean	ASD 16	ADT 46	Mean
N1 - NU @ 1 %	32.69	36.76	34.73	5.18	5.04	5.11
N2 - NU @ 2 %	33.16	35.29	34.23	5.14	5.12	5.13
N3 - NU @ 3 %	35.84	36.72	36.28	5.07	5.18	5.13
N4 - NU @ 4 %	34.20	34.7	34.45	5.21	5.16	5.19
N5 - Neem-coated urea @0.25 %	37.36	38.82	38.09	5.24	5.12	5.18
N6 - Neem-coated urea @ 0.5 %	39.10	39.14	39.12	5.27	5.16	5.22
N7 - Neem-coated urea @ 1 %	38.84	37.20	38.02	5.22	5.23	5.23
N8 - RDF	32.28	36.56	34.42	4.72	5.03	4.88
N9 - Absolute control (0 % N)	31.27	34.03	32.65	4.51	4.62	4.57
Mean	34.97	36.58		5.06	5.08	

	N	V	V@N	N@V
		SPAD		
SED	1.24	2.72	3.81	3.35
CD (0.05)	3.57	4.21	5.16	5.02
		LAI		
SED	0.05	0.52	1.12	1.47
CD (0.05)	1.31	1.17	2.43	2.81

the critical vegetative growth period (20-40 DAS). The relationship between LAI and yield components was highly significant in NCU-treated plots, where the expanded canopy architecture improved light interception efficiency by 15 %-18 % compared to NU treatments (33). This photosynthetic advantage had a direct effect on biomass accumulation, with NCU treatments showing 10 %-12 % increased dry matter output at the flowering stage. This optimum LAI (5.375 m^2 m^{-2}) for the RDF control indicated the importance of extended nitrogen availability for good canopy development (34). Although split applications are required in typical RDF practice, this capability is inherent to NCU's release pattern. These results demonstrate how NCU can simplify nitrogen management while maintaining or improving canopy performance achieved by more labour-intensive split application regimes.

Yield attributing parameters

The characteristics of the panicles revealed significant reactions to nitrogen treatments; formulations of NU were outperformed by NCU and RDF. A key indicator of yield potential, panicle length was greatest under RDF (mean of 24.52 cm) and then NCU at 0.5 % (mean of 22.56 cm), which was much greater than NU treatments (17.52 cm-17.86 cm). This is consistent and found that standard urea increased panicle length in rice by 18 %-25 % when compared to slow-release formulations. This was explained by longer-lasting nitrogen availability during reproductive growth. Different sink capacities are reflected in ADT46's better performance than ASD16, which is in accordance with research on panicle architectural genes in indica types. The most direct yield component, the number of grains per panicle, increased by 59.8 % from control (122.2) to RDF (195.5), with NCU at 0.5 % hitting 93.3 % of RDF performance (181.2 grains) (Table 3).

Particularly noticeable was the V × N interaction, in which ADT46 reacted more strongly to larger N dosages (205.9 grains under RDF compared to 185.0 grains under ASD16). This supports showing that spikelet fertility is increased by 12 %-15 % when ammonium-dominated nutrition (such as from NCU) is used instead of nitrate-dominated sources. Through isotope labelling investigations shown that the physiological foundation is enhanced cytokinin translocation to panicles during grain filling (35). With better N management, chaffiness (unfilled grains) reduced exponentially, from 24.4 % in the control group to 7.0 % in the RDF. Using 15N tracer methods, reported that NU at 3 % exhibited 32.4 % more chaffiness than NCU at 0.5 % (13.2 % vs. 9.7 %). This is probably because of early N depletion during grain filling. The varietal difference in chaffiness (15.1 % for ADT46 vs. 12.1 % for ASD16) can be due to

Table 3. Panicle length, No. of filled and unfilled grains/panicle of rice as influenced by the application of NU and NCU

Treatment	Panicle length (cm)			No. of filled grains/panicle			Chaffiness		
	ASD 16	ADT 46	Mean	ASD 16	ADT 46	Mean	ASD 16	ADT 46	Mean
N1 - NU @ 1 %	16.29	18.74	17.52	116.04	134.52	125.28	15.23	19.82	17.53
N2 - NU @ 2 %	17.67	17.97	17.82	123.04	141.81	132.43	12.08	17.23	14.66
N3 - NU @ 3 %	17.58	18.13	17.86	127.00	149.47	138.24	11.72	14.71	13.22
N4 - NU @ 4 %	17.89	17.56	17.73	132.56	143.65	138.11	12.63	16.27	14.45
N5 - NCU @ 0.25 %	19.53	20.34	19.94	158.70	165.93	162.32	8.12	12.92	10.52
N6 - NCU @ 0.5 %	21.86	23.25	22.56	173.34	189.12	181.23	9.91	9.53	9.72
N7 - NCU @ 1 %	20.15	21.59	20.87	166.85	178.91	172.88	11.51	10.43	10.97
N8 - RDF	16.23	17.78	17.01	118.69	138.80	128.75	18.53	19.52	19.03
N9 - Absolute control (0 % N)	15.42	16.67	16.05	108.03	120.93	114.48	21.38	27.43	24.41
Mean	18.07	19.11		136.03	151.46		13.46	16.43	

	N	V	V@N	N@V
		Panicle length		
SED	0.76	0.56	1.26	1.56
CD	1.84	1.67	2.83	2.73
		No. of filled grains/panicle		
SED	3.56	4.37	5.62	3.48
CD	8.12	8.78	10.86	7.86
		Chaffiness		
SED	1.16	1.21	2.32	2.18
CD	2.73	2.72	5.16	4.61

ADT46's larger sink area, which necessitates more accurate N timing.

Grain yield

Significant differences in grain production between various nitrogen treatments are shown by the experimental data. Applications of NCU (N5-N7:) performed better than NU treatments (N1-N4: 3.62-3.87 t ha^{-1}) and the absolute control (N9: 3.27 t ha^{-1}), with mean yields ranging from 4.445 to 4.7 t ha^{-1} (36). The RDF produced the maximum grain yield (N8: 5.05 t ha^{-1}), followed by 0.5 % NCU (N6: 4.7 t ha^{-1}). NCU's improved performance is due to its slow-release nitrogen mechanism, which lowers losses from leaching, volatilization and increases NUE. Neem's azadirachtin ingredient prolongs nitrogen availability throughout crucial growth phases by acting as a nitrification inhibitor (13) (Table 4).

Straw yield

The foliar application of NCU treatments (N5-N7) resulted in higher straw yields (5.36-5.41 t ha^{-1}) compared to NU (N1-N4, 4.87-5.02 t ha^{-1}), RDF (N8, 5.29 t ha^{-1}) and the absolute control (N9, 5.10 t ha^{-1}). This aligns with previous research indicating that NCU enhances NUE, leading to improved straw production in rice cultivation. In contrast, NU treatments exhibited lower straw yields, consistent with recent findings suggesting that NU may reduce straw biomass (37). The highest straw yield was observed with NCU at 0.5 % (N6, 5.36 t ha^{-1}), reinforcing its effectiveness in promoting vegetative growth. These results highlight the superior performance of NCU over NU and conventional RDF in enhancing straw yield under the Tamirabarani river basin conditions (Table 4).

Agronomic nitrogen use efficiency

The NUE analysis revealed significant variations across different treatments and rice varieties. The maximum overall NUE for both kinds was shown by the RDF (N8) treatment, with 58.2 % for ASD16 and 66.0 % for ADT46. NCU treatments performed better than NU applications. The 0.5 % concentration (N6) produced the highest NUE among NCU treatments (48.9 % for ASD16 and 62.4 % for ADT46), suggesting that this dosage produced the best nitrogen utilization. Among NU applications, the 4 % concentration (N4) demonstrated the best performance (20.8 % for ASD16 and 36.5 % for ADT46), with NU treatments displaying somewhat lower NUE values (27) (Fig. 2). Significantly, ADT46 continuously performed better than ASD16 in terms of nitrogen consumption in all treatments, especially in grain NUE, indicating variations in the efficiency of nitrogen intake and assimilation between varieties. In order to maximize NUE in rice production, these results emphasize the significance of both fertilizer type and concentration. NCU at

Table 4. Grain yield and straw yield of rice as influenced by the application of NU and NCU

Treatment		**Grain yield (t/ha)**			**Straw yield (t/ha)**		
		ASD 16	**ADT 46**	**Mean**	**ASD 16**	**ADT 46**	**Mean**
N1 - NU @ 1 %		3.42	3.82	3.62	4.53	5.46	5.00
N2 - NU @ 2 %		3.71	3.88	3.80	4.62	5.34	4.98
N3 - NU @ 3 %		3.83	3.91	3.87	4.53	5.21	4.87
N4 - NU @ 4 %		3.69	3.98	3.84	4.59	5.45	5.02
N5 - NCU @0.25%		4.32	4.57	4.45	5.05	5.67	5.36
N6 - NCU @ 0.5 %		4.58	4.82	4.70	5.18	5.54	5.36
N7 - NCU @ 1 %		4.41	4.64	4.53	5.38	5.44	5.41
N8 - RDF		4.96	5.14	5.05	5.24	5.34	5.29
N9 - Absolute control (0 % N)		3.12	3.42	3.27	4.76	5.44	5.10
Mean		4.00	4.24		4.87	5.43	
	N		**V**		**V@N**		**N@V**
			Grain yield				
SED	0.13		0.11		0.26		0.36
CD (0.05)	0.27		0.22		0.56		0.61
			Straw yield				
SED	1.24		0.21		0.28		0.32
CD (0.05)	2.91		0.44		0.61		0.72

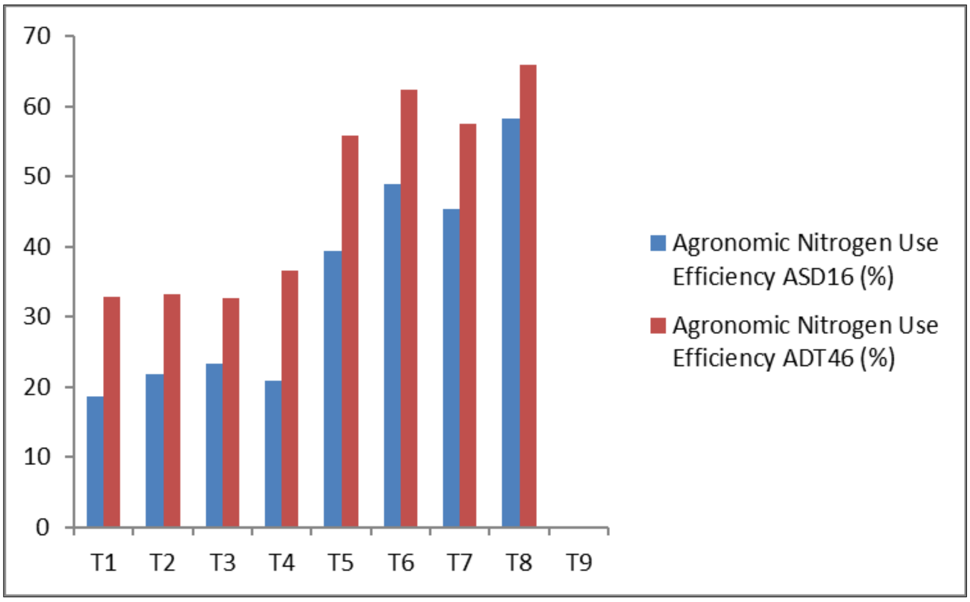

Fig. 2. Agronomic NUE of ASD 16 and ADT 46 as influenced by the application of NU and NCU.

intermediate concentrations (0.25 %-0.5 %) demonstrated especially encouraging results.

Conclusion

In terms of agronomic performance, NCU was superior to NU throughout the *Rabi* season (December 2023 to April 2024), which was characterized by moderate temperatures and limited precipitation. Although ideal application conditions are crucial for the foliar efficacy of NU, NCU's slow-release mechanism and nitrification inhibition offered more consistent nitrogen supply, leading to increases in grain and straw yields of 20.6 % and 8.2 % respectively. The much greater nitrogen-use efficiency of NCU was demonstrated by the 39.4 % increase in grain output compared to the unfertilized control. Due to being susceptible to environmental losses, field observations showed that NU performed inconsistently, while NCU's combined advantages of controlled nitrogen release and pest-repellent qualities enhanced yield stability and nutrient retention. According to these results, foliar-applied NCU may provide a more environmentally friendly fertilizer approach for locations like the Tamirabarani Basin, especially those that are subjected to water scarcity and runoff. In order to create scalable, financially feasible suggestions for farmers, future research should concentrate on improving application procedures and combining NCU with precision farming methods.

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Authors' contributions

ED participated in the research activities, field establishment, statistical data analysis and the writing of the research article. SJ, KB, PSP, MJ and SS edited and reviewed the research article. ED participated in data analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors have no conflicts of interest to disclose.

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Grammarly in order to improve the language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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