PLANT SCIENCE TODAY
Vol 13(sp1): 01–13
https://doi.org/10.14719/pst.10101

eISSN 2348-1900

RESEARCH ARTICLE

Assessing urea efficiency in paddy using vegetation indices: A comparative study of super nano urea and conventional urea

Gayathri P[1]*, Muthumanickam D[1], Pazhanivelan S[2], Kannan P[3], Kumaraperumal R[1] & Prabu P C[2]

[1]Department of Remote Sensing and Geographic Information System, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Centre for Agricultural Nanotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - gayathriprabhakaran124@gmail.com

Received: 17 June 2025; Accepted: 12 August 2025; Available online: Version 1.0: 12 January 2026

Cite this article: Gayathri P, Muthumanickam D, Pazhanivelan S, Kannan P, Kumaraperumal R, Prabu PC. Assessing urea efficiency in paddy using vegetation indices: A comparative study of super nano urea and conventional urea. Plant Science Today. 2026;13(sp1):01–13. https://doi.org/10.14719/pst.10101

Abstract

This study evaluates the efficiency of solid and liquid Super Nano Urea (SNU) and conventional urea in rice, focusing on physiological responses, grain quality and vegetation indices. A field experiment during *Rabi* and *Kharif* 2024 compared 13 fertilization strategies, including 100 %, 75 % and 50 % of the Recommended Dose of Nitrogen (RDN) using SNU granules, with or without two foliar sprays of 0.7 % liquid SNU at tillering and panicle initiation stages. Parallel treatments used conventional urea at equivalent nitrogen (N) levels, also with and without foliar sprays. A no-fertilizer control was included. Growth parameters such as Plant Height (PH), Leaf Area Index (LAI), Soil Plant Analysis Development (SPAD) values and vegetation indices including Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge Index (NDREI), Ratio Vegetation Index (RVI) and Green Normalized Difference Vegetation Index (GNDVI), were recorded. The results showed that foliar application of SNU significantly enhanced Nitrogen Use Efficiency (NUE). For instance, SNU at 100 % RDN + 2 sprays yielded 6318 kg ha^{-1}, versus 6150 kg ha^{-1} without sprays. Similarly, conventional urea at 100 % + 2 sprays produced the highest yield (6400 kg ha^{-1}), outperforming its no-spray counterpart (6273 kg ha^{-1}). Foliar sprays improved nutrient uptake, panicle traits and Grain Yield (GY). Despite limited distribution and regulatory hurdles for SNU, the results show that combining conventional urea with foliar sprays provides a high-performing, sustainable nitrogen management strategy.

Keywords: conventional fertilizer; foliar spray; SNU; sustainability; vegetation indices

Introduction

Rice (*Oryza sativa* L.), the world's staple food crop, is a source of food security, human health and nutrition. About 60 % of the world's population depends on rice. World rice production was 216 million tonnes in 1961 and rose to 769 mt in 2020 (1). The 2023 – 2024 rice area harvested was 165.69 million hectares, with an average yield of 4.7 t ha^{-1}, yielding around 515.83 million tonnes. India attained an average yield of 4.32 t ha^{-1}, yielding 137 million tonnes from 47.6 million hectares. India accounts for around 20 % of global rice production and the major rice-producing states are Uttar Pradesh, West Bengal, Punjab, Tamil Nadu and Telangana. In Tamil Nadu, the rice area was around 4.7 million hectares, yielding 7.85 million tonnes (2).

Nitrogen is essential for crop growth, playing a vital role in photosynthesis, biomass production and GY (3). However, inefficient N use contributes significantly to environmental pollution, including greenhouse gas emissions and water contamination (4). In India, NUE is only about 33 %, while fertilizer consumption has surged since the 1960s, raising concerns about sustainability. To address this, improving NUE is critical for achieving both high agricultural productivity and environmental protection. Various strategies have been proposed to enhance NUE, including integrated nitrogen management, which combines chemical, organic and bio-fertilizers (3).

Advanced approaches such as site-specific nutrient management, leaf colour charts and remote sensing tools are used to more precisely assess and meet crop N requirements. Balanced fertilization, split applications, nitrification inhibitors and slow-release fertilizers further contribute to efficient N use (5). Nitrogen fertilizer, needed for plant growth, poses environmental issues when used excessively (6). Recent innovations, such as nano urea, especially when combined with traditional urea, have shown promise in improving yield and profitability, as seen in wheat and rice systems (7). Spatially guided interventions encompassing agronomic, economic and policy aspects are necessary to optimize N application (7). These strategies aim to support food security while minimizing N inputs and environmental damage, thereby promoting a sustainable, resilient cereal production system.

Nano fertilizers, particularly Nano-Nitrogen Fertilizers (NNFs), have been identified as a promising solution to improve NUE and advance sustainable agriculture. Nanomaterial's ensure site-specific nutrient delivery, enhanced plant uptake and smaller environmental footprints than conventional fertilizers (8). NNFs have been reported to increase crop yields by 10-80 % , extend N release rates and reduce application rates (9). They facilitate achieving sustainable development goals by increasing nutrient uptake efficiency and reducing environmental losses. Alleviate issues such as nutrient leaching, volatilization and greenhouse gas emissions associated with conventional fertilizers. However, additional research is needed to fully elucidate their mechanisms, justify formulations and assess potential impacts on human health and food chains.

However, the use of new technologies such as remote sensing and machine learning has increased the potential to optimize N management at a larger scale, offering wider and more efficient means of fertilizing in rice production (10). Remote sensing technologies, especially multispectral and hyper spectral imaging, facilitate the non-destructive measurement of crop health and nutrient status. By recording canopy reflectance at varying wavelengths, these technologies can provide useful information on the crop's N status and other physiological parameters (11).

Recently, the Indian Farmers Fertiliser Cooperative (IFFCO) developed and patented (Indian patent application numbers 201921053828 and 201921044499) a nano-fertiliser, i.e., nano-urea, for use as an alternative to commercial urea. The fertilizer nano-urea is of particle size in nanometres (nm) in one dimension (at least 50 % of the material), physical particle size between 20 and 50 nm and hydrodynamic particle size between 20 and 80 nm. Nano-urea has 4 % N, a shelf-life of approximately 2 years and a zeta potential > 30 (12).

It includes functional nutrients obtained mainly from urea, which are treated with non-ionic surfactants and additionally stabilized in polymer matrices to form nano clusters < 100 nm. The synthesized Nano-fertilizer was experimented with in laboratory conditions and small plot studies to validate its efficacy (12,13). The efficiency of IFFCO developed nano-urea was validated based on multi-location (11000 locations) and multi-crop (94 crops) trials in varied crop seasons, both by researchers and forward looking farmers in India. The use of nano-urea has been found to increase yields in wheat (14-16), maize (17) and Indian mustard (18-20) at the locations.

Research on the development of Nano-fertilizers has been explored for the past two decades by different researchers, institutes and organizations (8). The new Nano-fertilizers are thought to create a paradigm shift in agriculture (21). There are very few instances in which nanotechnology has moved from the laboratory to the field, and even fewer in which it has been implemented at the commercial scale (22). This study examines the use of SNU in solid form under field conditions for rice cultivation, as it was previously available only in liquid form.

This research aims to explore the current state of knowledge regarding the impact of SNU (solid and spray) and conventional urea application in rice fields and to shed light on innovative approaches that hold promise for sustainable, environmentally friendly rice farming practices. Through a comprehensive examination of existing literature and emerging research, this study seeks to provide valuable insights into the role of nano urea in shaping the future of rice cultivation, with optimal fertilizer application in the context of climate change mitigation.

Materials and Methods

Experimental site and climate conditions

The experiment was conducted in field no. M3 and M4 of the wetland farm, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu and India. The geographical location of the experimental site was categorized under the Western agroclimatic zone of Tamil Nadu, situated at 11° N latitude and 77° E longitude and at an altitude of 426.7 m above mean sea level (Fig. 1). Throughout the experimental year (2024), meteorological data regarding daily temperature and rainfall were recorded. The standard weekly weather data for the experimental period (2024) was sourced from the TNAU meteorological observatory, located close to the experimental site (Supplementary Table 1 & 2). The soil at the site was well-drained, non-saline, slightly alkaline (pH 7.9) and had a clay loam texture. The experimental site was situated in a semi-arid region with an average annual precipitation of 736 mm and the details of the field experiments are given in Table 1.

Experimental design and details

The experimental trial was laid out in a Randomized Block Design (RBD) with 13 treatments and three replications, including a control (Fig. 2, Table 2). The plot size of 5 m in length and 7 m in width was maintained uniformly across all treatments within each replication. The detailed soil characteristics are given in Supplementary Table 3. Nursery bed preparation was done. The nursery bed was 6 m x 1.5 m. The rice variety used in this experiment was ADT 53. A summary of its key agronomic traits is presented in Table 3. Seeds were soaked in

Fig. 1. Representing the locations of the experimental site of the paddy crop field.

Table 1. Details of the field experiment

Rabi season-2024		*Kharif* season-2024	
Date of sowing	28.01.2024	**Date of sowing**	25.06.2024
Date of transplanting	14.02.2024	**Date of transplanting**	13.07.2024
Date of harvest	17.04.2024	**Date of harvest**	30.09.2024
Duration	116 days	**Duration**	119 days

Fig. 2. Layout of experimental plot.

Table 2. The treatment details of the experiment

T_1 - 100 % RDN through SNU (15 kg ha^{-1})
T_2 - 75 % RDN through SNU (11.25 kg ha^{-1})
T_3 - 50 % RDN through SNU (7.5 kg ha^{-1})
T_4 - T_1 + 2 spray of SNU at the rate of 0.7 % during tillering and PI stages
T_5 - T2 +2 spray of SNU at the rate of 0.7 %
T_6 - T3 +2 spray of SNU at the rate of 0.7 %
T_7 - 100 % RDFN (150 kg ha^{-1})
T_8 - 75 % RDFN (112.5 kg ha^{-1})
T_9 - 50 % RDFN (75 kg ha^{-1})
T_{10} - T_7+2 spray of SNU at the rate of 0.7 %
T_{11}- T_8+2 spray of SNU at the rate of 0.7 %
T_{12}- T_9+ 2 spray of SNU at the rate of 0.7 %
T_{13}- Control (No NPK)

*Spraying stages: Tillering and Panicle initiation stage

*P and K were applied to all the treatments as per the CPG recommendation

Table 3. Characteristics of ADT 53

Particulars	**ADT 53**
Parentage	ADT 43 x JGL 384
Duration	110 - 115 days
Season	Kar/ Kuruvai/ Navarai/ Summer
Days to 50 % flowering	80-85
Average grain yield (kg ha^{-1})	6334
Thousand grain weight (g)	14.8
Grain type	Medium slender
Colour of grain	White
Salient features	High milling out turn with intermediate amylose, moderately resistant to blast, sheath rot, brown plant hopper and leaf folder

water for 24 hr and pre-germinated by placing them in the shade the next day. On the day after, 20 kg of seeds were sown in 9 beds. The experimental field was ploughed. At the time of puddling, keep water to a depth of 2.5 cm. The field was then levelled and plots were set out according to the layout design. The experimental location had 39 plots, with each replication consisting of 13 plots. The treatments were assigned to the plots at random. In each plot over the bund, a polythene sheet was used to cover the area and prevent seepage movement of water from the treatment plot to the adjacent plots.

Fertilizer application

The fertilizer recommendation for the rice variety ADT 53 under the Coimbatore tract was 150:50:50 NPK kg ha^{-1}. The sources of N, phosphorus (P) and potassium (K) were urea, Single Super Phosphate (SSP) and Muriate of Potash (MOP), respectively. Nitrogenous fertilizers were applied according to the treatments. Phosphorus was applied as basal at the time of transplanting. Potassium was applied in four splits: a basal application and applications at the active tillering, panicle initiation and heading stages.

Details of foliar spray

The required quantity of foliar nutrient and its spray volume were calculated and applied uniformly to the treatments using a battery-operated sprayer. The details of foliar nutrition are given in Table 4.

Nano Urea Plus is a higher-concentration nano urea (20 % N w/v). It has N in the form of urea-amide, ammoniacal, aminos, etc. As it is nano-sized (<100 nm), it has a higher surface area-to-volume ratio, allowing it to distribute more evenly across the crop's foliage. This allows effective N assimilation and results in improved chlorophyll and photosynthetic efficiency, as well as improved crop yield and quality. It was sprayed at 0.7 % (7 mL L^{-1}) in the treatment plots at the respective stages, as per the treatment details.

Table 4. The details of the foliar nutrition

S. No.	Treatment	Concentration	Application time
1.	Nano urea plus 0.7 % at active tillering, at panicle initiation and heading stages	7 mL L^{-1} of water	35 DAT, 55 DAT and 75 DAT (Active tillering stage, panicle initiation stage, maturity stage)

Nutrient composition of fertilizers

Urea (N) = 46 %

Single Super Phosphate (P_2O_5) = 16 %

Muriate of Potash (K_2O) = 60 %

Data acquisition of spectral signature and estimation of vegetation indices

The study used the GER 1500 spectroradiometer to measure the spectral reflectance of rice plants treated with various fertilizer combinations, including solid SNU and conventional urea. This instrument covers wavelengths from 350 to 1050 nm, encompassing the UV, visible and Near-Infrared (NIR) regions. Measurements were taken at 1.5-3.2 nm bandwidth intervals using a silicon diode array, with the device positioned 1 meter above the plant canopy and a 4° field-of-view laser targeting the foliage. Calibration was performed using a white reference board to account for ambient light conditions. Data acquisition occurred under bright sunlight between 11:00 and 13:00 IST to simulate field conditions. Readings were taken for vegetation index measurements with a Spectroradiometer in Fig. 3.

Spectral signatures, which represent the reflectance patterns of surfaces across different wavelengths, were recorded for each of the 39 plots. Healthy vegetation typically absorbs blue and red light while reflecting green light in the visible spectrum (400-700 nm) and reflecting strongly in the NIR region (700-1300 nm) due to internal cell structures. Differences in spectral signatures between rice plants treated with SNU and those with conventional urea can indicate variations in chlorophyll content, leaf structure, or water content, providing insights into plant health and fertilizer efficacy.

Measurement of growth, yield attributes and yield

Various growth characteristics, including PH and LAI, as well as yield-related factors such as number of Effective Tillers per Hill (ETH), Panicles per Hill (PPH), Grains per Panicle (GP), Panicle Length (PL), Thousand-Grain Weight (TGW), GY, Straw Yield (SY) and Harvest Index (HI), were measured and assessed. This analysis aimed to gauge the impact of different N fertilizer application levels and cultivation techniques, to gather insights that could guide strategic choices to improve rice production. These attributes provide insights into the performance, productivity and quality of the rice crop. PH was measured at different growth stages, including the active tillering, panicle initiation and maturity stages. To capture variations within each plot, multiple plant samples were randomly selected and PH was measured from the base to the tip of the longest leaf using a measuring tape. Harvesting was conducted when the rice plants reached maturity, characterized by physiological maturity and grain moisture content within the recommended range. The rice plants from each plot were harvested, threshed to separate the grains from the straw and cleaned to remove impurities. Grain yield was determined by weighing the harvested grains after drying to a constant moisture content. Biomass yield was calculated by weighing the straw collected from each plot. Harvest index was calculated using the following formula:

$$\text{Harvest index} = \frac{\text{Economic yield (kg ha}^{-1})}{\text{Biological yield (kg ha}^{-1})} \qquad \text{(Eqn. 1)}$$

Where,

Economic yield = Grain yield; Biological yield = Grain yield + Straw yield

LAI measurement

The third leaf from the top was used for leaf area measurement at 20, 35, 55 and 75 DAT. Leaf area was determined with a leaf area meter (Model LI-3100C). This device allows for accurate and efficient measurement of leaf area and monitoring of leaf growth and development. LAI was calculated using the following standardized formula (23):

$$\text{LAI} = \frac{\text{Total leaf area per plant (cm)}^{2}}{\text{Ground leaf area per plant (cm)}^{2}} \qquad \text{(Eqn. 2)}$$

Statistical analysis

The data collected, such as vegetation indices, growth and yield attributes, underwent rigorous statistical analysis to derive important findings using the Statistical Packages for Social Sciences (SPSS) software (24). Analysis of Variance (ANOVA) was used to determine the significance of variation between N fertilizer applications, including nano-urea and conventional urea production techniques. To determine the applicability of the observed results, the *p*-value of ≤ 0.05 was utilized. When statistically significant discrepancies were observed, Duncan's Multiple Range Test (DMRT) was used to identify the specific differences between treatments. Moreover, Standard Error (SE) was employed to measure the degree of variability in individual data values.

Fig. 3. Vegetation index measurement with spectroradiometer.

Results and Discussion

Impact of SNU vs conventional urea on plant growth

The application of additional foliar sprays significantly affected PH at harvest. Specifically, the SNU 100 % treatment with two sprays resulted in a 7.20 % increase in PH compared to the solid SNU 100 % treatment without sprays. Similarly, the Conventional 100 % treatment with two sprays showed a 4.44 % enhancement compared to its counterpart without sprays. Compared with the control group, which had a PH of 82.20 cm at harvest, the SNU 100 % + 2 sprays treatment achieved a 12.29 % increase in PH. In contrast, the conventional 100 % + 2 sprays treatment demonstrated a more substantial increase of 22.99 % over the control. Among all treatments, the conventional 100 % + 2 sprays regimen yielded the highest PH at harvest, measuring 101.10 cm. This indicates that the combination of full conventional nutrient application with two additional foliar sprays is the most effective strategy for maximizing PH. The SNU 100 % + 2 sprays treatment also showed significant improvement, underscoring the positive impact of supplementary foliar applications on plant growth. The Control group, with no fertilizer or sprays, consistently shows the lowest PH across all stages, highlighting the importance of nutrient application for optimal growth. For season 2, among all treatments, the Conventional 100 % + 2 sprays regimen yielded the highest PH at harvest, measuring 99.10 cm, as shown in Table 5 & 6. This indicates that the combination of full conventional nutrient application with two additional foliar sprays is the most effective strategy for maximizing PH. The SNU 100 % + 2 sprays treatment also showed significant improvement, underscoring the positive impact of supplementary foliar applications on plant growth.

PH differed considerably within treatments at all growth stages, the tallest being under the conventional 100 % + 2 spray treatment (101.1 cm at harvest in season 1), followed by conventional 100 % (96.8 cm). This is a manifestation of the enhancing effect of optimal soil fertilization and nutrient spraying on vegetative development. Sufficient N supply is responsible for cell division and elongation, which results in taller plants (25). The enhanced height registered by SNU 100 % + 2 spray (92.3 cm) over reduced levels of SNU indicates the significance of nutrient adequacy and the contribution of foliar application to improve nutrient use efficiency.

Recent studies have demonstrated the potential of nano-fertilizers to enhance crop growth and nutrient use efficiency. Foliar application of nano-zinc and nano-urea improved PH, dry matter accumulation and nutrient uptake in Indian mustard (26). However, as nanotechnology in agriculture is still in its early stages, further research is needed to fully understand its effects and optimize application methods across various crops and growing conditions.

Table 5. Impact of SNU vs conventional urea on plant growth

Treatments	Plant height season 1			
	Before spray	Active tillering stage	Panicle initiation stage	Harvest stage
SNU 100 %	20.93	39.90	65.23	86.10
SNU 75 %	16.96	34.20	54.50	85.00
SNU 50 %	12.93	32.40	51.00	83.50
SNU 100 % + 2 spray	19.06	42.86	73.84	92.30
SNU 75 % + 2 spray	15.33	40.06	67.49	87.50
SNU 50 % + 2 spray	11.40	36.33	59.52	86.02
Conventional 100 %	28.06	47.86	75.95	96.80
Conventional 75 %	23.73	41.93	69.00	88.30
Conventional 50 %	18.90	33.93	53.49	84.50
Conventional 100 % + 2 spray	26.86	49.06	93.60	101.10
Conventional 75 % + 2 spray	21.86	44.73	75.63	93.60
Conventional 50 % + 2 spray	13.20	37.96	60.24	86.10
Control	10.46	31.46	49.28	82.20
SE(d)	0.90	1.90	3.16	7.13
CD (P= 0.05)	1.80	3.92	6.54	11.53

Table 6. Impact of SNU vs conventional urea on plant growth

Treatments	Plant height (cm) season 2			
	Before spray	Active tillering stage	Panicle initiation stage	Harvest stage
SNU 100 %	19.93	36.9	61.23	80.1
SNU 75 %	15.96	31.2	50.5	79
SNU 50 %	11.93	29.4	47	77.5
SNU 100 % + 2 spray	18.06	39.86	69.84	86.3
SNU 75 % + 2 spray	14.33	37.06	63.49	81.5
SNU 50 % + 2 spray	10.4	33.33	55.52	80.02
Conventional 100 %	27.06	44.86	71.95	90.8
Conventional 75 %	22.73	38.93	65	82.3
Conventional 50 %	17.9	30.93	49.49	78.5
Conventional 100 % + 2 spray	25.86	46.06	89.6	95.1
Conventional 75 % + 2 spray	20.86	41.73	71.63	87.6
Conventional 50 % + 2 spray	12.2	34.96	56.24	80.1
Control	9.46	28.46	45.28	76.2
SE(d)	0.8	1.7	2.9	3.9
CD (P= 0.05)	1.7	3.62	6.1	8.2

Impact of SNU vs conventional urea on LAI

By comparing the differences in LAI between treatments to the corresponding CD values, researchers can identify which treatments have a meaningful impact on LAI at different growth stages. This approach ensures that conclusions drawn about treatment efficacy are supported by statistical evidence, enhancing the reliability of the study's findings.

Here is the result analysis of LAI data across various treatments and growth stages: Conventional 100 % + 2 sprays of SNU consistently recorded the highest LAI values at all growth stages, reflecting superior crop vigour and leaf development. Solid SNU 100 % + 2 sprays showed improved LAI compared with SNU alone but did not match those of conventional treatments. Foliar sprays increased LAI across all N levels, especially in the 75 % and 50 % N treatments. Reduced N (50 %) levels, particularly in SNU treatments, resulted in significantly lower LAI values, thereby affecting potential biomass accumulation. Control plots had the lowest LAI across all stages, indicating N deficiency's impact on canopy development. The LAI values shown in Fig. 4.

LAI rose gradually with crop growth, reaching a peak at panicle initiation, in accordance with earlier research indicating that maximum LAI is reached prior to the reproductive stage (27). The peak LAI under the conventional 100 % + 2 spray treatment (3.81) highlighted the synergy between optimal fertilization and foliar sprays, which amplify canopy growth by delivering nutrients during critical periods (25). The marginally decreased LAI in the conventional 100 % treatment (3.64) further supported the influence of soil nutrient adequacy, while enhanced performance in the SNU +

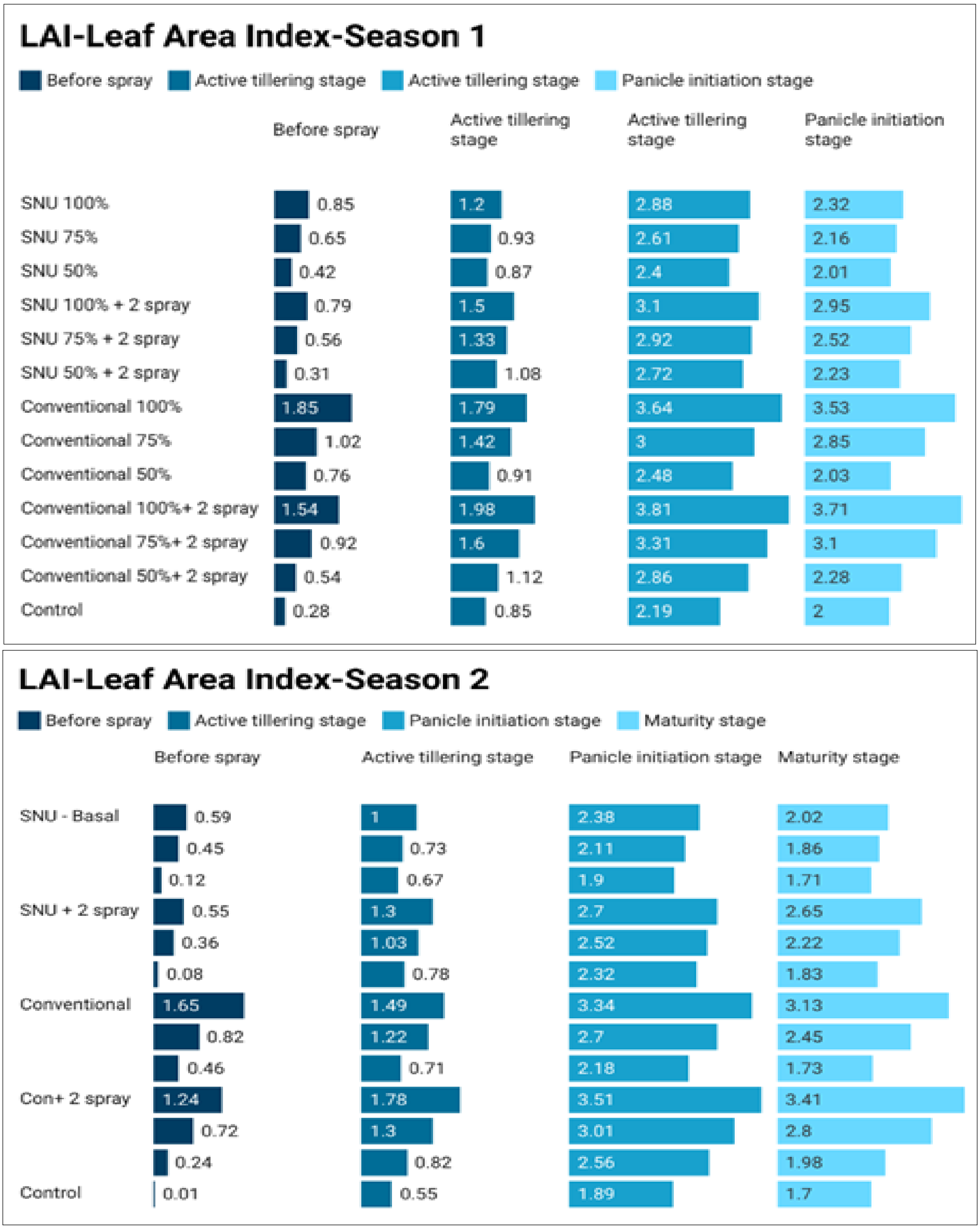


Fig. 4. Impact of super nano urea vs conventional urea on LAI.

spray treatments indicates that foliar application enhances the efficacy of smart nutrient utilization strategies (28). The control had the lowest LAI, indicating limited nutrient supply and poor canopy growth (29). Overall, combining soil fertilization with foliar sprays effectively promoted canopy growth and sustainable yield increases.

Impact of SNU vs conventional urea on SPAD value

Analysis and summary of SPAD chlorophyll meter readings across different treatments and crop growth stages are detailed: Conventional 100 % + 2 sprays yielded the highest SPAD values across all stages, indicating better N assimilation and sustained chlorophyll content. SNU 100 % + 2 sprays improved SPAD readings compared to SNU alone but still fell short of conventional treatments. Sprays significantly improved SPAD, especially at the panicle initiation and harvest stages. Lower N levels (50 %) resulted in reduced SPAD values in Fig. 5, especially without foliar supplementation. Control plots had the lowest chlorophyll content, confirming N deficiency.

Chlorophyll concentration, as expressed by SPAD values, was maximum in the conventional 100 % + 2 spray treatment (50.02 during panicle initiation and 37.08 at harvest), which indicates the close relationship between N supply and chlorophyll production (30). Nitrogen is an integral part of chlorophyll molecules and its sufficient supply from soil and foliar applications most probably helped in improving the photosynthetic capacity and retarding senescence (31). The enhanced SPAD readings for SNU + spray treatments relative to their respective basal applications document the positive influence of foliar feeding to supplement N during critical growth. Nevertheless, traditional practices consistently performed better than SNU-based practices, indicating that, though smart nutrient strategies work, their effectiveness may be limited at high crop nutrient requirements unless supplemented with additional inputs. The findings highlight the importance of integrated nutrient management for maintaining chlorophyll content and, consequently, crop productivity.

Impact of SNU vs conventional urea on vegetation indices of paddy

Impact of nitrogen levels

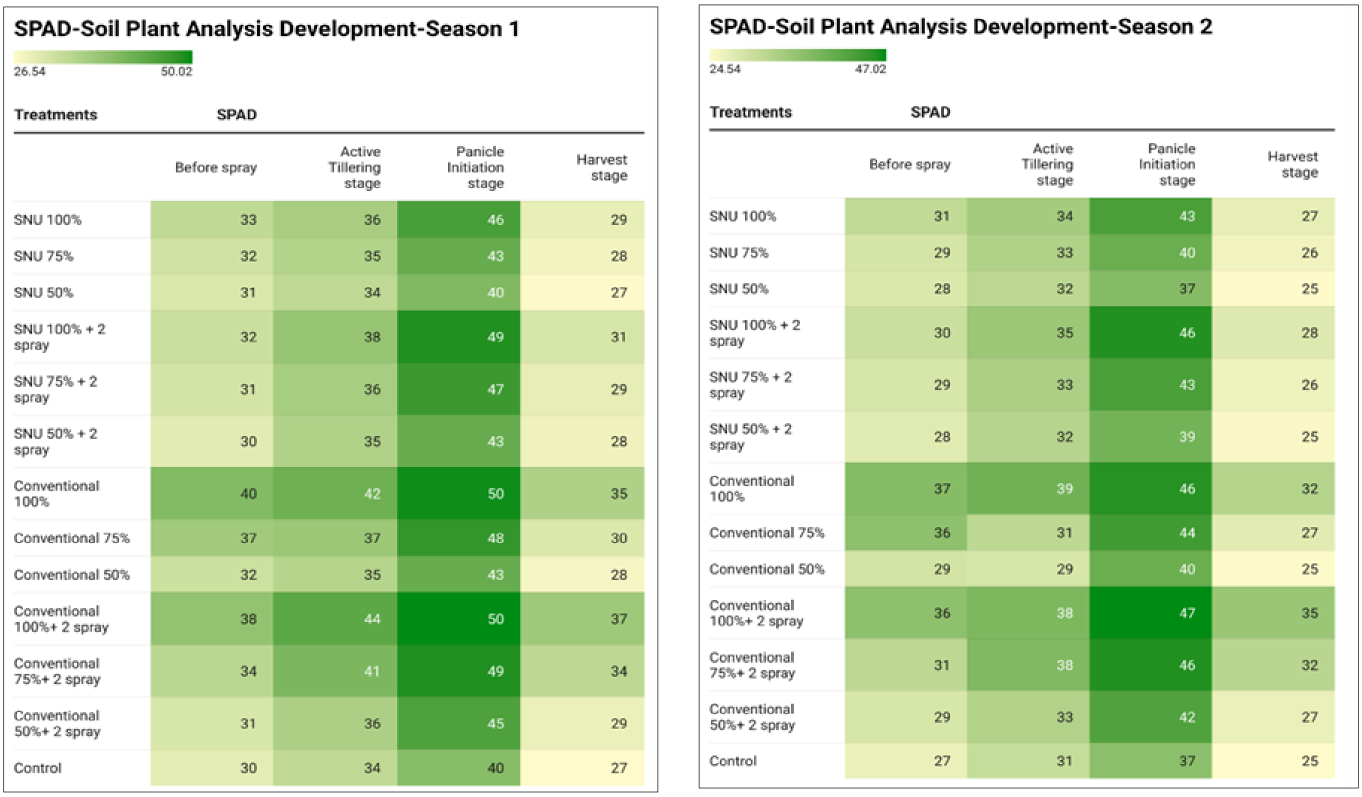
SNU treatments: As N levels decreased from 100-50 %, there was a consistent decline in all vegetation indices. For instance, NDVI dropped from 0.198-0.067, indicating reduced plant vigour with lower N availability. This trend aligned with findings that increasing N application enhanced vegetation indices such as NDVI, GNDVI, RVI and NDREI, reflecting improved plant health and productivity.

Conventional treatments: Similarly, reducing N from 100-50 % lead to decreased indices. NDVI decreased from 0.268-0.148 and GNDVI from 0.47-0.27, reflecting diminished chlorophyll content and photosynthetic activity. Impact of SNU vs conventional urea on vegetation indices of paddy is shown in Table 7 & 8. These observations were consistent with studies showing that higher N levels correlate with increased vegetation indices, indicating better crop performance.

Effect of additional sprays

SNU with sprays: Adding two sprays enhances vegetation indices across all N levels. In this experiment, SNU 100 % + 2 sprays shows an NDRE of 0.58 compared to 0.47 in SNU 100 % without sprays, suggesting improved N status and chlorophyll content. This improvement is supported by research indicating that supplemental treatments can boost vegetation indices, reflecting enhanced plant health.

Conventional with sprays: The addition of sprays also boosts indices. Conventional 100 % + 2 sprays have a GNDVI of 0.49, compared with 0.47 in conventional 100 %, indicating enhanced plant health. Such enhancements align with findings that additional treatments can positively influence vegetation indices, signifying improved crop vigour.



SPAD-Soil Plant Analysis Development-Season 1

26.54 – 50.02

Treatments	SPAD			
	Before spray	Active Tillering stage	Panicle Initiation stage	Harvest stage
SNU 100%	33	36	46	29
SNU 75%	32	35	43	28
SNU 50%	31	34	40	27
SNU 100% + 2 spray	32	38	49	31
SNU 75% + 2 spray	31	36	47	29
SNU 50% + 2 spray	30	35	43	28
Conventional 100%	40	42	50	35
Conventional 75%	37	37	48	30
Conventional 50%	32	35	43	28
Conventional 100%+ 2 spray	38	44	50	37
Conventional 75%+ 2 spray	34	41	49	34
Conventional 50%+ 2 spray	31	36	45	29
Control	30	34	40	27

SPAD-Soil Plant Analysis Development-Season 2

24.54 – 47.02

Treatments	SPAD			
	Before spray	Active Tillering stage	Panicle Initiation stage	Harvest stage
SNU 100%	31	34	43	27
SNU 75%	29	33	40	26
SNU 50%	28	32	37	25
SNU 100% + 2 spray	30	35	46	28
SNU 75% + 2 spray	29	33	43	26
SNU 50% + 2 spray	28	32	39	25
Conventional 100%	37	39	46	32
Conventional 75%	36	31	44	27
Conventional 50%	29	29	40	25
Conventional 100%+ 2 spray	36	38	47	35
Conventional 75%+ 2 spray	31	38	46	32
Conventional 50%+ 2 spray	29	33	42	27
Control	27	31	37	25

Fig. 5. Impact of Super Nano urea vs conventional urea on SPAD value.

Table 7. Impact of SNU vs conventional urea on vegetation indices of paddy

Treatment	Vegetation indices in season 1															
	NDVI				RVI				NDRE				GNDVI			
	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS
SNU 100 %	0.22	0.44	0.63	0.46	4.3	6.7	9.5	14	0.18	0.22	0.27	0.31	0.27	0.32	0.41	0.43
SNU 75 %	0.14	0.38	0.57	0.39	3.5	6.2	8.8	13.1	0.15	0.19	0.24	0.28	0.24	0.29	0.38	0.38
SNU 50 %	0.089	0.31	0.51	0.36	3.2	5.4	8.3	12.7	0.12	0.17	0.22	0.26	0.21	0.27	0.36	0.36
SNU 100 % + 2 spray	0.18	0.56	0.74	0.54	4	7.3	10.3	14.9	0.17	0.25	0.31	0.34	0.26	0.35	0.44	0.46
SNU 75 % + 2 spray	0.12	0.47	0.68	0.48	3.4	6.8	9.8	14.3	0.14	0.23	0.28	0.32	0.23	0.33	0.42	0.44
SNU 50 % + 2 spray	0.053	0.39	0.59	0.41	3	6.3	9	13.4	0.11	0.2	0.25	0.29	0.2	0.3	0.39	0.4
Conventional 100 %	0.29	0.61	0.79	0.57	5	7.6	10.7	15.9	0.22	0.27	0.33	0.36	0.31	0.37	0.46	0.5
Conventional 75 %	0.25	0.52	0.71	0.53	4.7	7.1	10.1	14.7	0.2	0.24	0.3	0.33	0.29	0.34	0.43	0.45
Conventional 50 %	0.17	0.34	0.54	0.37	3.9	5.9	8.6	12.9	0.16	0.18	0.23	0.27	0.25	0.28	0.37	0.37
Conventional 100 % + 2 spray	0.27	0.65	0.82	0.59	4.9	7.9	10.9	16.3	0.21	0.28	0.34	0.37	0.3	0.38	0.47	0.51
Conventional 75 % + 2 spray	0.23	0.59	0.77	0.56	4.5	7.4	10.5	15.2	0.19	0.26	0.32	0.35	0.28	0.36	0.45	0.49
Conventional 50 % + 2 spray	0.11	0.42	0.62	0.43	3.3	6.5	9.2	13.8	0.13	0.21	0.26	0.3	0.22	0.31	0.4	0.42
Control	0.024	0.26	0.48	0.32	2.9	5.1	8.2	12.2	0.1	0.16	0.21	0.25	0.19	0.26	0.33	0.34

Table 8. Impact of SNU vs conventional urea on vegetation indices of paddy

Treatment	Vegetation indices in season 2															
	NDVI				RVI				NDRE				GNDVI			
	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS	Before spray	30 DAS	60 DAS	90 DAS
SNU 100 %	0.198	0.33	0.47	0.36	3.7	6.5	9.3	14.8	0.19	0.23	0.28	0.32	0.28	0.33	0.41	0.42
SNU 75 %	0.118	0.27	0.41	0.29	3.3	5.7	8.6	13.8	0.16	0.19	0.25	0.29	0.24	0.29	0.37	0.39
SNU 50 %	0.067	0.2	0.35	0.26	2.9	5.2	8.3	13.9	0.13	0.17	0.22	0.26	0.21	0.26	0.34	0.36
SNU 100 % + 2 spray	0.158	0.45	0.58	0.44	4.5	7.4	10.3	15.8	0.18	0.26	0.32	0.35	0.27	0.36	0.44	0.45
SNU 75 % + 2 spray	0.098	0.36	0.52	0.38	3.9	6.9	9.5	15.2	0.15	0.24	0.29	0.33	0.23	0.34	0.42	0.43
SNU 50 % + 2 spray	0.031	0.28	0.43	0.31	3.4	6.1	8.9	14	0.12	0.2	0.26	0.3	0.19	0.31	0.39	0.4
Conventional 100 %	0.268	0.5	0.63	0.47	4.8	7.9	10.8	16.2	0.23	0.28	0.34	0.37	0.32	0.38	0.47	0.49
Conventional 75 %	0.228	0.41	0.55	0.43	4.2	7.2	9.8	15.6	0.21	0.25	0.31	0.34	0.3	0.35	0.43	0.44
Conventional 50 %	0.148	0.23	0.38	0.27	3.1	5.4	8.4	13.4	0.17	0.18	0.24	0.27	0.25	0.28	0.35	0.37
Conventional 100 % + 2 spray	0.248	0.54	0.66	0.49	5	8.2	11	16.4	0.22	0.29	0.35	0.38	0.31	0.39	0.48	0.52
Conventional 75 % + 2 spray	0.208	0.48	0.61	0.46	4.6	7.7	10.6	16	0.2	0.27	0.33	0.36	0.29	0.37	0.46	0.47
Conventional 50 % + 2 spray	0.088	0.31	0.46	0.33	3.6	6.3	9.1	14.5	0.14	0.21	0.27	0.31	0.22	0.32	0.4	0.41
Control	0.002	0.15	0.32	0.22	2.8	4.9	8.1	12.1	0.09	0.15	0.2	0.24	0.18	0.25	0.33	0.35

Comparison between SNU and conventional treatments

At equivalent N levels, Conventional treatments generally exhibit higher vegetation indices than SNU treatments. For instance, the conventional 75 % has an NDVI of 0.228, surpassing the SNU 75 % at 0.118, suggesting better plant vigour under conventional practices. This disparity may be attributed to differences in fertilizer formulations and application methods, which can influence nutrient availability and uptake.

Control group performance: The Control group consistently recorded the lowest values across all indices (e.g., NDVI: 0.002), underscoring the need for N and spray applications for optimal plant health. This underscores the critical role of nutrient management in sustaining crop vigour and productivity.

Vegetation indices such as NDVI, RVI, NDRE and GNDVI were most significant with the conventional 100 % + 2 spray treatment, indicating increased chlorophyll content and biomass production. These indices are well known to be sensitive to canopy structure, greenness and photosynthetic activity (32).The high values for foliar-supplemented treatments indicated enhanced crop vigour resulting from increased nutrient availability, specifically N, which immediately affected chlorophyll production and leaf area expansion (33). The low index values in the control and the limited fertilizer treatments, on the other hand, indicate poor canopy development and below-optimum plant health. The findings confirm the value of vegetation indices as accurate, non-destructive indicators of crop nutrient status, biomass accumulation and plant health in real time (34). In such scenarios, therefore, coupling foliar nutrition with traditional fertilization not only reinforces physiological characteristics but also enhances remote-sensing-based crop evaluation.

Spectral signature

Rice plants treated with SNU exhibited spectral signatures that differed clearly from those of plants treated with conventional urea. These differences, indicative of variations in chlorophyll concentration, leaf morphology or water content, were measured using a field-portable spectroradiometer.

The curve showed that higher reflectance in the crops coincided with treatments such as 100 % Recommended Dose of Fertilizer Nitrogen (RDFN) with 2 sprays of SNU at 0.7 %, which also showed higher reflectance. The capability and sensitivity of detecting crop growth status and vegetation indices are frequently utilized. It is a crucial method for monitoring plant stress in agriculture. The spectral signature was recorded at three growth stages: 30 Days After Transplanting (DAT), 60 DAT and 90 DAT to capture the spectral reflectance of the rice canopy. Healthy plants exhibited very high reflectance in the NIR region, typically between 700 nm and 1300 nm, resulting from the spongy mesophyll internal leaf structure, which efficiently scatters NIR light. This NIR reflectance was largely decoupled from pigments and was instead driven by cellular architecture, making it a key indicator of leaf structure and canopy biomass. These spectral characteristics, low visible (blue/red) reflectance, moderate green reflectance and very high NIR are sensitive to chlorophyll concentration, leaf internal structure and water content. Thus, variations in these bands can reveal physiological differences such as stress, pigment degradation, or hydration levels between treatments. The capability and sensitivity of detecting crop growth status and vegetation indices are frequently utilized. At this point, the enhanced N uptake from SNU is expected to have manifested as elevated chlorophyll levels, altered leaf microstructure and modified canopy water status. spectral signature variations in rice under SNU and Conventional Urea Applications are shown graphically in Fig. 6. These physiological and structural changes led to distinctive reflectance patterns, especially in the green, red-edge and NIR regions, enabling precise discrimination between SNU and conventional urea treatments.

Impact of nitrogen levels on yield attributes

SNU and conventional treatments both showed a clear decline in performance as N levels decreased from 100-50 %. Solid SNU treatments, filled GP dropped from 74.7 (100 %) to 49.6 (50 %) and GY decreased from 6150-5573 kg ha^{-1}. Similarly, conventional treatments dropped from 83.2-42.4 in filled grains and from 6273-5635 kg ha^{-1} in GY. This indicates that N availability directly influences panicle development, grain filling and ultimately GY.

Effect of additional sprays

Adding two foliar sprays significantly boosted the performance across all N levels: In SNU 100 % + 2 spray, GY increased to 6318 kg ha^{-1}, higher than SNU 100 % without spray (6150 kg ha^{-1}), as shown in Fig. 7. Similarly, Conventional 100 % + 2 spray yields 6400 kg ha^{-1}, compared to 6273 kg ha^{-1} without sprays. Sprays likely enhanced N uptake or nutrient assimilation, improving PL, weight and overall productivity.

Comparison: SNU vs conventional

At the same N level, conventional treatments consistently outperformed SNU: conventional 75 % yield = 6013 kg ha^{-1}; SNU 75 % = 5881 kg ha^{-1}; Conventional 50 % yield = 5635 kg ha^{-1}; SNU 50 % = 5573 kg ha^{-1}. This suggests that conventional SNU fertilization methods may be more efficient or better optimized than SNU alone in this context.

Control group performance

The control group (no fertilizer or sprays) performed worst in all aspects: Filled grains: 20.6, Panicle weight: 10.3 g, GY: 4714 kg ha^{-1}, as shown in Fig. 8. This confirms that both N and spray applications are critical to maximizing crop yield and panicle development.

Statistical significance

Many yield attributes (except 1000 g test weight) showed statistical significance at $p = 0.05$. The Critical Difference (CD) values indicate where treatments differ significantly and a GY difference of > 523 kg ha^{-1} is significant. Higher N levels, especially when combined with foliar sprays, lead to better yield attributes and productivity. Conventional practices tend to outperform SNU and the absence of N or sprays drastically reduces performance.

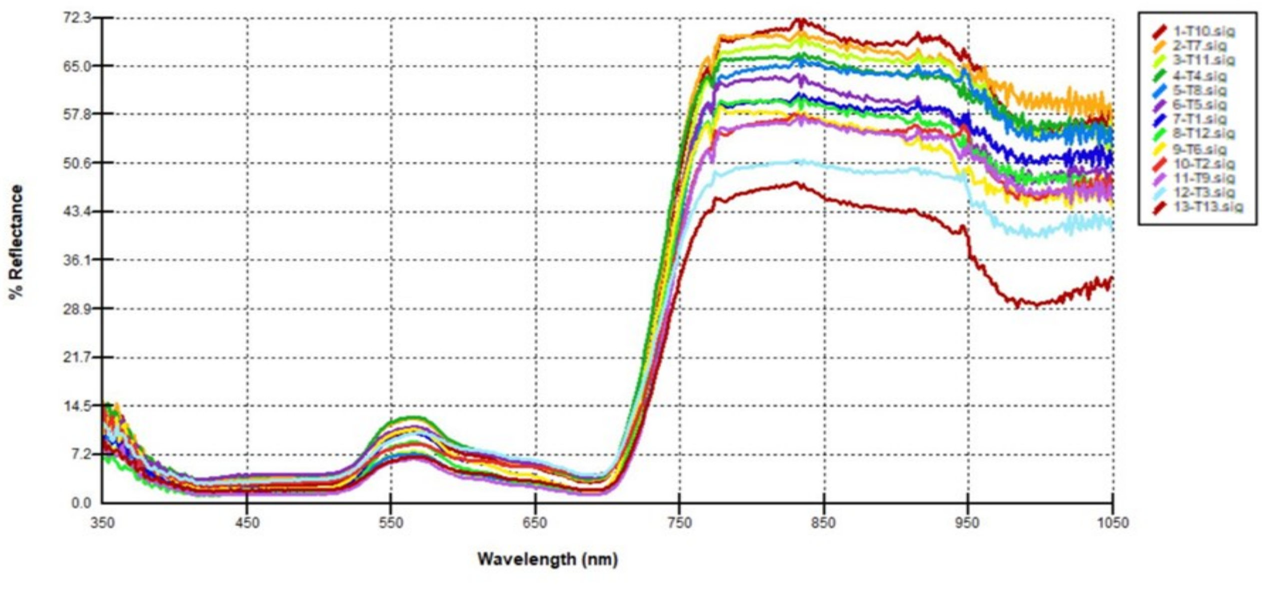


Fig. 6. Spectral signature variations in rice under super nano urea and conventional urea applications.

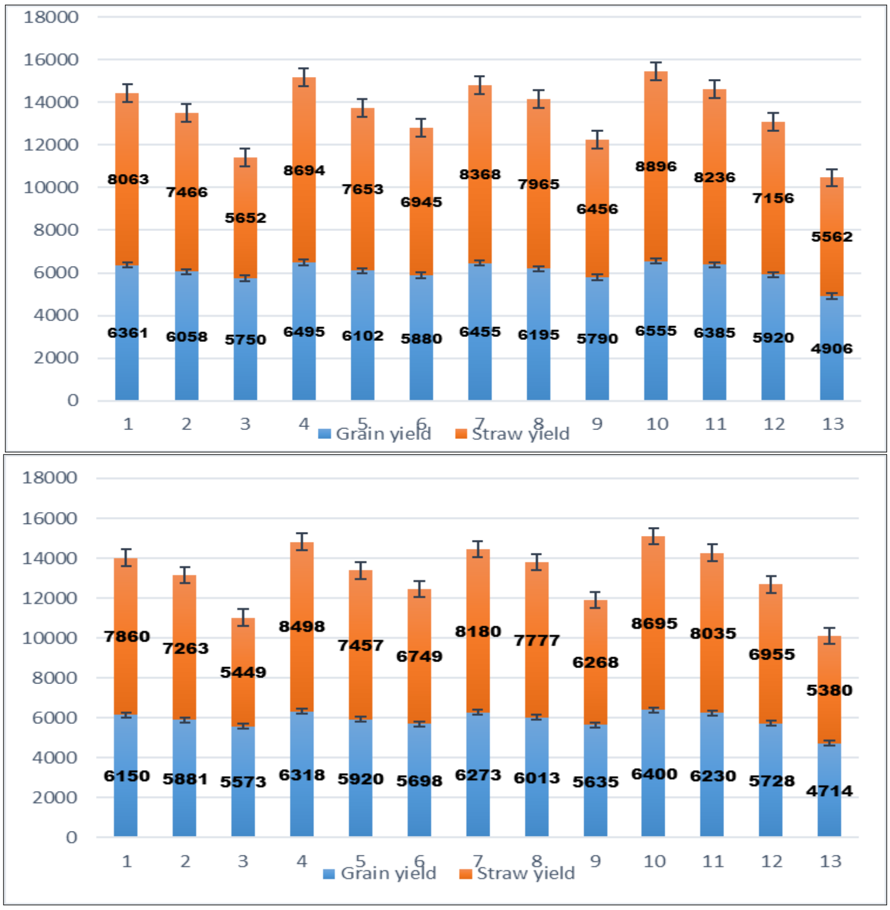


Fig. 7. Impact of nitrogen levels on grain and straw yield.

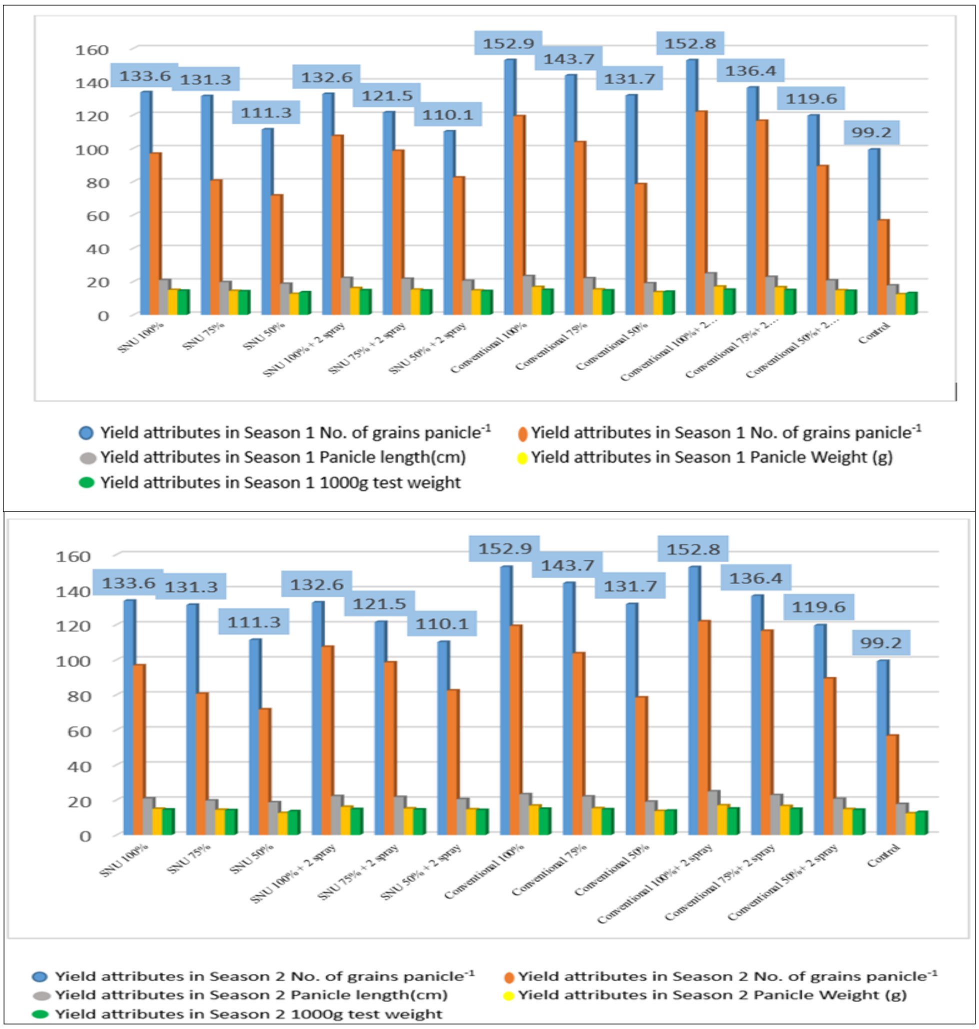


Fig. 8. Impact of nitrogen levels on yield attributes.

Yield attributes and grain yield

The GY and SY were considerably greater following the conventional 100 % + 2 spray treatment (6555 and 8896 kg ha^{-1}, respectively), reflecting the synergistic effect of maximum soil fertilization and foliar nutrient application. This treatment also improved yield attributes such as PL, number of GP, filled grains and TGW, underscoring the importance of balanced nutrition in enhancing both source (photosynthetic capacity) and sink (grain filling) traits (35). The SNU 100 % + 2 spray treatment also worked well, demonstrating that intelligent nutrient-use strategies, when supplemented with foliar feeding, can achieve nearly optimal productivity. The control treatment yielded the least (4906 kg ha^{-1}), underscoring the utmost importance of proper and timely nutrient supply for ensuring crop development and reproductive growth (36). These findings confirmed that integrated nutrient management not only enhanced vegetative and physiological variables but also directly equated to increased yield and economic gain.

Comparative performance: SNU vs conventional

While conventional treatments outperformed SNU treatments across most parameters, the SNU 100 % + 2 spray treatment approached the performance of the conventional 100 % treatment, suggesting that optimized SNU practices supplemented with foliar feeding could be a sustainable alternative.

This highlights that, with optimized application timing and strategic foliar supplementation, SNU can serve as a viable, sustainable alternative. The broader literature supports this, demonstrating that foliar-applied nano fertilizers can maintain or even enhance crop yields while reducing N input by 20-30 %. Further on-farm trials and life-cycle assessments are needed to comprehensively quantify the cost-benefit ratio, ecological footprint and scalability of the SNU 100 % + 2-spray system under diverse agro-climatic conditions. Establishing best-practice guidelines will be key to translating these promising results into sustainable agricultural solutions. Environmentally, nano-urea reduces N runoff and leaching and greenhouse gas emissions, while enhancing nutrient use efficiency and soil health. Economically, it can lower input costs and improve farmer profitability despite potentially higher upfront product prices.

Conclusion

This study highlights the crucial impact of nutrient management and foliar application on rice growth and productivity. SNU formulations often have lower N content than conventional urea, potentially affecting crop nutrition. As a newer product, SNU faces distribution limitations and ongoing regulatory evaluations. Foliar spraying significantly enhanced the effectiveness of both conventional and SNU-based treatments. While conventional full-dose fertilization remained superior, conventional 100 % + 2 spray emerged as a promising, sustainable approach, balancing yield with a potentially reduced environmental footprint. In summary, while SNU offers innovative approaches to fertilization, addressing these challenges is crucial for its sustainable adoption in agriculture.

Acknowledgements

The authors would like to thank the Department of Remote Sensing and GIS and the Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, for providing the necessary facilities and support for writing this paper. We also extend our gratitude to our colleagues who provided valuable feedback and suggestions to improve the manuscript.

Authors' contributions

GP contributed to the study conception, literature survey, data collection and writing of the original draft. MD was involved in data collection and data curation and processing were performed by MD. PS validated the collected data and contributed to the literature survey. KR participated in the literature survey and reviewed the manuscript for quality. KP contributed to writing the original draft of the manuscript. PPC assisted in the study conception and revised the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

AI declaration

The authors used ChatGPT (OpenAI) to assist with proofreading and refining the grammar and style of the final draft. While the core ideas and original writing remain entirely our own, the AI tool helped polish the language and enhance readability. All AI-suggested modifications were thoroughly reviewed and revised by the authors to ensure alignment with our intended meaning.

References

1. Food and Agriculture Organization of the United Nations. World food and agriculture - statistical yearbook 2023. Rome; 2023.
2. Childs N, LeBeau B, Vaiknoras K. Rice Outlook: January 2024. Washington (DC): U.S. Department of Agriculture, Economic Research Service; 2024
3. Amanullah, Ullah H. Boosting crop growth rates of hybrid rice (Pukhraj) through synergistic use of organic nitrogen sources in conjunction with urea nitrogen. Nitrogen. 2024;5(1):28-46. https://doi.org/10.3390/nitrogen5010003
4. Zahoor A, Christy M, Hwang YJ, Lim YR, Kim P, Nahm KS. Improved electrocatalytic activity of carbon materials by nitrogen doping. Appl Catal B Environ. 2014;147:633-41. https://doi.org/10.1016/j.apcatb.2013.09.043
5. Govindasamy P, Muthusamy SK, Bagavathiannan M, Mowrer J, Jagannadham PTK, Maity A, et al. Nitrogen use efficiency-a key to enhance crop productivity under a changing climate. Front Plant Sci. 2023;14:1121073. https://doi.org/10.3389/fpls.2023.1121073
6. Yadav D, Shivay Y, Singh Y, Sharma V, Bhatia A. Enhancing nutrient translocation, yields and water productivity of wheat under rice-wheat cropping system through zinc nutrition and residual effect of green manuring. J Plant Nutr. 2020;43(19):2845-56. https://doi.org/10.1080/01904167.2020.1798997
7. Kumari M, Tomar B, Singh P, Tomar SS, Patle T, Parihar SS.

Nanotechnology and agricultural sustainability: environmental impacts and benefits. In: Harnessing nanoOmics and nanozymes for sustainable agriculture. IGI Global; 2024. p. 176-92. https://doi.org/10.4018/979-8-3693-1890-4.ch009

8. Sapkota TB. India's fertilizer policies: implications for food security, environmental sustainability and climate change. Reg Environ Change. 2025;25(2):1-13. https://doi.org/10.1007/s10113-025-02395-9
9. Verma KK, Song XP, Degu HD, Guo DJ, Joshi A, Huang HR, et al. Recent advances in nitrogen and nano-nitrogen fertilizers for sustainable crop production: a mini-review. Chem Biol Technol Agric. 2023;10(1):111. https://doi.org/10.1186/s40538-023-00488-3
10. Abhiram G. Contributions of nano-nitrogen fertilizers to sustainable development goals: a comprehensive review. Nitrogen. 2023;4(4):397-415. https://doi.org/10.3390/nitrogen4040028
11. Iatrou M, Karydas C, Iatrou G, Pitsiorlas I, Aschonitis V, Raptis I, et al. Topdressing nitrogen demand prediction in rice crop using machine learning systems. Agriculture. 2021;11(4):312. https://doi.org/10.3390/agriculture11040312
12. Blekanov I, Molin A, Zhang D, Mitrofanov E, Mitrofanova O, Li Y. Monitoring of grain crops nitrogen status from UAV multispectral images coupled with deep learning approaches. Comput Electron Agric. 2023;212:108047. https://doi.org/10.1016/j.compag.2023.108047
13. Kumar Y, Singh T, Raliya R, Tiwari K. Nano fertilizers for sustainable crop production, higher nutrient use efficiency and enhanced profitability. Indian J Fert. 2021;17(11):1206-14.
14. Raliya R, Saharan V, Dimkpa C, Biswas P. Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. J Agric Food Chem. 2017;66(26):6487-503. https://doi.org/10.1021/acs.jafc.7b02178
15. Behboudi F, Tahmasebi Sarvestani Z, Kassaee MZ, Modares Sanavi S, Sorooshzadeh A. Improving growth and yield of wheat under drought stress via application of SiO_2 nanoparticles. J Agric Sci Technol 2018;20(7):1479-92.
16. Al-Juthery H, Hardan H, Al-Swedi FG, Obaid M, Al-Shami Q. Effect of foliar nutrition of nano-fertilizers and amino acids on growth and yield of wheat. In: IOP Conference Series: Earth and Environmental Science; 2019; Bristol, UK: IOP Publishing; 2019. p. 012046. https://doi.org/10.1088/1755-1315/388/1/012046
17. Du W, Yang J, Peng Q, Liang X, Mao H. Comparison study of zinc nanoparticles and zinc sulphate on wheat growth: from toxicity and zinc biofortification. Chemosphere. 2019;227:109-16. https://doi.org/10.1016/j.chemosphere.2019.03.168
18. Manikandan A, Subramanian K. Evaluation of zeolite based nitrogen nano-fertilizers on maize growth, yield and quality on inceptisols and alfisols. Int J Plant Soil Sci. 2016;9(4):1-9. https://doi.org/10.9734/IJPSS/2016/22103
19. Arora S, Sharma P, Kumar S, Nayan R, Khanna P, Zaidi M. Gold-nanoparticle induced enhancement in growth and seed yield of *Brassica juncea*. Plant Growth Regul 2012;66:303-10. https://doi.org/10.1007/s10725-011-9649-z
20. Das A, Babu S, Yadav G, Ansari M, Singh R, Baishya L, et al. Status and strategies for pulses production for food and nutritional security in north-eastern region of India. Indian J Agron 2016;61:43-57.
21. Rathore S, Shekhawat KA, Singh R, Updhyay P, Shekhawat R, Premi O. Effect of nano-particles on growth, productivity, profitability of Indian mustard (*Brassica juncea*) under semi-arid conditions. Indian J Agric Sci 2019;89:1145-50. https://doi.org/10.56093/ijas.v89i7.91669
22. Khattak WA, Ullah MW, Manan S, Islam SU, Khattak WA, Ul-Islam M. Emerging applications and future trends of agri-nanotechnology. In: Shahzad R, Fiaz S, Qayyum A, Ul Islam M, Lee IJ, editors. Revolutionizing agriculture: a comprehensive exploration of agri-nanotechnology. Cham: Springer; 2024. p. 429–58. https://doi.org/10.1007/978-3-031-76000-6_19
23. Mullen A. Expectations from nano in agriculture. Nat Nanotechnol 2019;14(6):515-6. https://doi.org/10.1038/s41565-019-0471-5
24. Patra K, Parihar CM, Nayak H, Rana B, Sena DR, Anand A, et al. Appraisal of complementarity of subsurface drip fertigation and conservation agriculture for physiological performance and water economy of maize. Agr Water Manage 2023;283:108308. https://doi.org/10.1016/j.agwat.2023.108308
25. SPSS I. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp; 2012.
26. Damor RI, Desai CK, Desai JS. Enhancing growth and yield of Indian mustard through foliar application of nano urea and nano zinc: a field study. Int J Res Agron. 2024;7(12S):236-8. https://doi.org/10.33545/2618060X.2024.v7.i12Sd.2139
27. Fageria NK. Nitrogen management in crop production. Boca Raton, FL: CRC Press; 2014 https://doi.org/10.1201/b17101
28. Boonjung H, Fukai S. Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions. 2. Phenology, biomass production and yield. Field Crops Res. 1996;48(1):47-55. https://doi.org/10.1016/0378-4290(96)00039-1
29. Zheng Y, Ding YF, Liu ZH, Wang SH. Effects of panicle nitrogen fertilization on non-structural carbohydrate and grain filling in indica rice. Agric Sci China. 2010;9:1630-40. https://doi.org/10.1016/S1671-2927(09)60260-1
30. Peng S, Garcia FV, Laza RC, Cassman KG. Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration. Agron J. 1993;85(5):987-90. https://doi.org/10.2134/agronj1993.00021962008500050005x
31. Yamori W. Photosynthetic response to fluctuating environments and photoprotective strategies under abiotic stress. J Plant Res 2016;129(3):379-95. https://doi.org/10.1007/s10265-016-0816-1
32. Gitelson AA, Merzlyak MN. Signature analysis of leaf reflectance spectra: algorithm development for remote sensing of chlorophyll. J Plant Physiol. 1996;148(3-4):494-500. https://doi.org/10.1016/S0176-1617(96)80284-7
33. Samborski SM, Tremblay N, Fallon E. Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. Agron J. 2009;101(4):800-16. https://doi.org/10.2134/agronj2008.0162Rx
34. Hatfield JL, Gitelson AA, Schepers JS, Walthall CL. Application of spectral remote sensing for agronomic decisions. Agron J 2008;100 Suppl:S117-31. https://doi.org/10.2134/agronj2006.0370c
35. Dobermann A, Fairhurst T. Rice: nutrient disorders and nutrient management. Los Baños (Philippines): Potash & Phosphate Institute; Potash & Phosphate Institute of Canada; International Rice Research Institute; 2000
36. Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C. Efficiency of fertilizer nitrogen in cereal production: retrospects and prospects. Adv Agron. 2005;87:85-156. https://doi.org/10.1016/S0065-2113(05)87003-8

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.