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RESEARCH ARTICLE

Effect of foliar nano urea plus combined with split nitrogen application on growth, physiological parameters and grain yield of finger millet (*Eleusine coracana* L.)

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Abstract

Nano-fertilizers are gaining attention as a sustainable strategy to optimize physiological performance and crop productivity. A field experiment was conducted during the summer and rabi seasons of 2024 at Tamil Nadu Agricultural University (TNAU), Coimbatore, to evaluate the effect of nano urea plus (NUP) on growth, physiological parameters and grain yield of transplanted finger millet. Twelve treatment combinations with varying nitrogen levels (recommended dose of fertilizer (RDF) and organic sources) with foliar NUP (0.75 %) sprays at tillering and panicle-initiation stages were evaluated. Nitrogen fertilization integrated with NUP significantly enhanced crop vigour, canopy development and biomass accumulation. At the final growth stage, 100 % RDF + one NUP spray (T_1) improved plant height by 35 %, leaf area index (LAI) by 60 %, normalized difference vegetation index (NDVI) by 35 % and growth indices-crop growth rate (CGR), relative growth rate (RGR) and absolute growth rate (AGR)-by 50 % compared to the absolute control, contributing to superior physiological efficiency. The same treatment also produced the highest grain yield (2588 and 2555 kg ha^{-1}) in both seasons. This performance was statistically comparable to 75 % RDF with two NUP sprays and 100 % RDF alone. These findings indicate that foliar application of NUP with optimal nitrogen application can strengthen nutrient-use efficiency and support sustainable nutrient management in finger millet production.

Keywords: biomass accumulation; crop growth indices; finger millet; foliar nano urea; yield

Introduction

Millets are resilient cereal grains belonging to the Poaceae family and are widely cultivated as small-seeded crops. Being photo-insensitive, C4 crops possess efficient carbon fixation mechanisms, enabling high productivity under heat and drought stress. This physiological advantage positions millets as climate-compliant crops and represents a sustainable and strategic alternative for ensuring food and nutritional security in the face of increasing climate variability and extreme weather events (1). Among them, finger millet (*Eleusine coracana* L.) stands out for its adaptability across diverse agro-climatic regions and its high nutritional value, particularly as a rich source of calcium and essential amino acids. It thrives in diverse agro-climatic conditions, requiring temperatures above 20 °C and altitudes exceeding 2400 m, with an annual rainfall of 350–400 mm (2). India ranks first globally in millet production, contributing 17.68 % to the total global output (3). Most of India's millet production comprises finger millet (ragi), sorghum (jowar) and pearl millet (bajra). In India, the area under finger millet cultivation is approximately 12.11 lakh ha, yielding 16.96 mt of production with a productivity of 1401 kg ha^{-1} (4). In Tamil Nadu, it is cultivated in 0.85 lakh ha, with a production of 2.56 lakh tonnes and a productivity of 2966 kg ha^{-1} (5).

With the increasing global food demand, modern agriculture has become heavily dependent on chemical fertilizers, especially nitrogen (6). Nitrogen is a vital macronutrient and a fundamental component of key primary and secondary metabolites in plants, including proteins, nucleic acids and chlorophyll (7). Consequently, nitrogen deficiency imposes a major limitation on plant growth and development, often resulting in substantial reductions in crop yield and overall productivity (8). However, the indiscriminate use of conventional fertilizers has resulted in environmental degradation, including soil deterioration, eutrophication, groundwater contamination and air pollution (9-12). Moreover, excessive fertilizer use has reduced the soil's intrinsic ability to supply essential macro and micronutrients, compounding the challenge of sustainable agricultural production. This deterioration not only limits yield

potential but also compromises grain nutritional quality, further intensifying concerns related to food security and public health (13). Addressing these inefficiencies in nitrogen use is therefore critical to both agricultural productivity and environmental sustainability.

Improving nutrient-use efficiency through nano-fertilizers has emerged as a promising strategy to balance productivity and environmental safety (14). To mitigate nutrient deficiencies in crops and enhance their nutritional value, while addressing environmental concerns, the integration of novel nano-fertilizers into agricultural systems is increasingly viewed as a transformative strategy (15). The integration of nano-fertilizers into agricultural systems represents a critical advancement toward achieving sustainability in both Indian and global contexts (16). By significantly enhancing nutrient-use efficiency, nano-fertilizers reduce the dependence on conventional chemical fertilizers. This reduction not only curtails nutrient losses through runoff and leaching but also lowers the greenhouse gas emissions associated with conventional practices. Collectively, these benefits contribute to environmentally sound, resource-efficient and climate-resilient agricultural development (17). Among various nanoformulations, nano-urea is gaining prominence as a sustainable alternative for nitrogen management in major cereals and millets.

Nano urea, a nanotechnology-based innovation, enhances nitrogen delivery in plants by improving translocation and assimilation, thereby promoting the synthesis of proteins and amino acids (18). Its controlled-release mechanism minimizes nitrogen losses via leaching and volatilization, thereby boosting nutrient efficiency and reducing environmental pollution (19). Notably, a 500 mL bottle of nano urea can match the efficacy of a conventional 45 kg urea bag, thus reducing dependency on bulk fertilizers, lowering input costs and improving environmental outcomes (20). Owing to their small size, unique morphology and enhanced reactivity, nano-fertilizers including nano urea, are increasingly recognized as high-value agricultural inputs (21). The integration of nano-enabled agriculture offers a sustainable solution to enhance crop productivity while curbing the environmental consequences of chemical fertilizers. While nano urea has shown promising results in cereals such as rice and wheat, its efficacy in minor millets like finger millet remains underexplored, warranting systematic evaluation under varied nutrient regimes (22).

Therefore, the present study was conducted to evaluate the effects of foliar nano urea plus (NUP), combined with varying nitrogen fertilizer regimes, on the growth, physiological performance and yield of finger millet, with the broader goal of advancing nutrient-efficient and environmentally sustainable farming practices. This study aligns with the United Nations Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), by promoting sustainable intensification and responsible nutrient management for resilient agricultural systems.

Materials and Methods

Experimental site

The field experiment was conducted in Field No. M9 at Wetland Farms, Department of Agronomy, Tamil Nadu Agricultural University (TNAU), Coimbatore, during the summer (March–May) and rabi (October–January) seasons. The site is located at 11.02° N latitude and 76.94° E longitude, at an altitude of 427 m above mean sea level, falling under the Western Agro-Climatic Zone of Tamil Nadu. Prior to experimentation, a composite soil sample was randomly collected from multiple locations within the field and analysed for physio-chemical properties. The soil was classified as clay loam, with detailed chemical characteristics presented in Table 1. The experiment was laid out in a randomized complete block design (RCBD) comprising twelve treatments and three replications. The crop was transplanted at a spacing of 30 × 10 cm. Each gross plot measured 4.0 m × 3.0 m (12 m^2), while the net plot area was 2.4 m × 3.8 m (9.12 m^2) to facilitate accurate observation and data collection.

Climate

For summer 2024, the experiment experienced 323.9 mm of rainfall over 22 rainy days, with mean maximum and minimum temperatures of 33.3 °C and 24.4 °C respectively. For rabi 2024, the site received 483.9 mm of rainfall across 25 rainy days and the mean maximum and minimum temperatures were 30.8 °C and 22.4 °C respectively.

Crop establishment and nursery management

Finger millet (Paiyur 2) seeds were procured from the Regional Research Station (RRS), Paiyur, Krishnagiri. This cultivar was selected due to its high yield potential and favourable agronomic traits, including compact, incurved fingers, uniform maturity, lodging resistance and moderate protein content (7.2 %). Nursery raising and main field operations were carried out following the Crop Production Guide recommendations (28). Seedlings were raised in nursery beds and uprooted at 17 days after sowing. Root inoculation was performed using *Bacillus subtilis*, following standard plant protection procedures as recommended in and seedlings were subsequently transplanted, targeting a plant density of approximately 33 plants m^{-2} (28). For biometric and physiological observations, five representative plants per plot were randomly sampled, excluding border rows to avoid edge effects.

Irrigation

Soaking irrigation was applied immediately after sowing and life-saving irrigation was provided on the third day after sowing. Thereafter, irrigation was scheduled based on rainfall data recorded at the meteorological observatory of TNAU, Coimbatore. The crop experiment was fully dependent on the precipitation received during the growing seasons, with totals of 335.1 mm in the summer 2024 and 472.7 mm in the rabi 2024 season.

Table 1. Chemical analysis of soil

Parameters	Authors	Methods	Summer 2024	Rabi 2024
Available nitrogen (kg ha^{-1})	(23)	Alkaline permanganate method	221.2	201.7
Available phosphorus (kg ha^{-1})	(24)	Olsen method	32.3	28.9
Available potassium (kg ha^{-1})	(25)	Neutral normal ammonium acetate method	460.3	449.4
pH	(26)	1:2 soil–water suspension	8.12	8.04
EC (dS m^{-1})		Conductivity meter	0.42	0.41
Organic carbon (%)	(27)	Chromic acid wet digestion method	0.34	0.32

Treatment details

Fertilizer application was conducted as per the prescribed treatment schedules. The recommended dose of fertilizer (RDF) of 60:30:30 kg N, P_2O_5 and K_2O per hectare was administered as urea (46 % N), single superphosphate (SSP; 16 % P_2O_5) and muriate of potash (MOP; 60 % K_2O). Full doses of phosphorus and potassium and one-third of nitrogen were applied basally at transplanting, while the remaining nitrogen was split equally and applied at tillering and panicle-initiation stages. NUP was applied as a 0.75 % foliar spray at the designated crop stages, depending on the treatment in Table 2 (29). The complete list of treatments is presented in Table 3. Farmyard manure (FYM) was applied on a nitrogen-equivalent basis using a nitrogen concentration of 0.5 %, as per standard analytical values. Accordingly, FYM quantities required to supply 100 %, 75 % and 50 % of the recommended nitrogen dose (60 kg N ha^{-1}) were calculated as 12.0, 9.0 and 6.0 t ha^{-1} respectively.

Plant height

Plant height was measured from the base to the tip of the uppermost leaf using a meter scale. Observations were recorded at 40, 60 and 90 days after transplanting (DAT) and at harvest from five randomly selected tagged plants per plot. Mean values were calculated and expressed in cm.

Leaf area index (LAI)

LAI was calculated at 30, 60, 90 DAT and at harvest from the same sample plants. It was calculated using the following formula (30):

$$LAI = \frac{L \times B \times K \times \text{number of green leaves hill}^{-1}}{\text{Spacing (cm)}}$$

Where,

L = length of the third leaf from the top (cm), B = width of the third leaf (cm) and K = constant factor (0.78)

Crop growth rate (CGR)

CGR was computed for the intervals 30–60, 60–90 DAT and 90 DAT–harvest using the standard growth analysis formula based on the dry matter of sampled plants (31). Above-ground biomass was oven-dried in a forced hot air oven (65 ± 2 °C) until constant weight and expressed as g m^{-2} day^{-1}.

$$CGR = \frac{W_2 - W_1}{t_2 - t_1} P$$

Where,

W_1 and W_2 represent the dry weight at time intervals t_1 and t_2 respectively and P denotes the area of ground occupied by the crop. CGR is expressed in g m^{-2} day^{-1}.

Relative growth rate (RGR)

RGR was determined following the standard logarithmic growth rate formula using the dry weights of plants at consecutive sampling intervals (20–40, 40–60 DAT and 60 DAT–harvest) (32). Values were expressed as g g^{-1} day^{-1}.

$$RGR = \frac{\ln W_2 - \ln W_1}{t_2 - t_1}$$

Where, W_1 and W_2 represent the dry weight at time intervals t_1 and t_2 respectively.

Absolute growth rate (AGR)

AGR represents the rate of increase in plant biomass or dry matter within a defined time interval. It was computed for each treatment using the standard formula (32) and expressed in g day^{-1}.

$$AGR = \frac{W_2 - W_1}{t_2 - t_1}$$

Where, W_1 and W_2 indicate the dry weight at time intervals t_1 and t_2 respectively.

Normalized difference vegetation index (NDVI)

NDVI was recorded at 30, 60 and 90 DAT using a hand-held GreenSeeker (Trimble Inc., USA) optical sensor. Measurements were taken around midday under uniform light conditions from multiple points within each plot, maintaining a constant height of 1 m above the canopy. NDVI values were used to assess crop vigour and nitrogen responsiveness.

Statistical analysis

Data recorded from field experiments during the summer and rabi seasons were subjected to statistical analysis. Treatment effects were evaluated using analysis of variance (ANOVA) performed with AGRES Statistical Software (version 7.01, TNAUSTAT) and treatment means were compared using the critical difference (CD)

Table 2. Physico-chemical characteristics of NUP

Formulation	Characteristics
Type	Liquid formulation
Manufacturer	IFFCO
Total nitrogen, percent by weight, minimum (%)	17.06
Hydrodynamic particle size as per by DLS (nm)	26.81 (D50)
Physical particle size as per TEM analysis (nm)	20.3
Appearance	Clear to slightly turbid transparent liquid dispersion
Mechanism	Compared to regular nano urea, NUP demonstrates higher leaf surface retention, longer foliar availability and better synchronization between nutrient release and crop demand

Table 3. Treatment details

T_1	100 % RDF + 1 spray of NUP 0.75 % during tillering
T_2	75 % RDF alone
T_3	75 % RDF + 1 spray of NUP 0.75 % during tillering
T_4	75 % RDF + 1 spray of NUP 0.75 % during panicle-initiation (PI)
T_5	75 % RDF + 2 sprays of NUP 0.75 % during tillering and PI stages
T_6	50 % RDF alone
T_7	50 % RDF + 2 sprays of NUP 0.75 % during tillering and PI stages
T_8	100 % organic on 'N' equivalent FYM + 1 spray of NUP 0.75 % during tillering
T_9	75 % organic on 'N' equivalent FYM + 2 sprays of NUP 0.75 % during tillering and PI stages
T_{10}	50 % organic on 'N' equivalent FYM + 2 sprays of NUP 0.75 % during tillering and PI stages
T_{11}	Control (100 % RDF alone) without NUP
T_{12}	Absolute control – No fertilizers and NUP

at the 5 % probability level. Differences that were not statistically significant were denoted as non-significant (NS). For multivariate analysis, recorded values were standardized using min–max normalization (scaling from 0 to 1) to minimize the influence of differing measurement units among traits. A hierarchical clustered heatmap was generated in RStudio (v4.5.1) using the heatmap package. Euclidean distance was used to compute pairwise similarities among treatments and clustering was performed using Ward's minimum variance method (hclust function).

Results

Foliar application of NUP, in combination with varying nitrogen levels, significantly influenced the growth, physiological responses and grain yield of finger millet during both summer and rabi seasons. The 100 % RDF + one NUP spray at tillering (T_1) consistently recorded superior values across all measured parameters, followed by 75 % RDF + two NUP sprays (T_5), while the absolute control (T_{12}) showed the lowest performance.

Growth parameter

The application of graded levels of NPK, organic nitrogen equivalents and foliar sprays of NUP significantly influenced the plant height of ragi during both the summer and rabi 2024 seasons (Table 4; Fig. 1). Treatment T_1 (100 % RDF + one NUP spray at tillering) recorded the tallest plants at harvest (136.9 cm in summer and 131.7 cm in rabi), showing an improvement of 35 % over the absolute control (T_{12}). Treatments T_5 (75 % RDF + two NUP sprays) and T_{11} (100 % RDF alone) were statistically comparable, indicating that even reduced RDF supplemented with foliar NUP sustained vigorous growth comparable to the full nitrogen dose.

Physiological parameters

Leaf Area Index (LAI)

The LAI, a vital indicator of the crop's photosynthetic surface, was markedly influenced by the application of graded nutrient sources and foliar sprays of NUP across the summer and rabi 2024 (Table 5). A natural decline in LAI was observed at harvest due to leaf senescence; however, T_1 (100 % RDF + one NUP spray at tillering) retained the highest LAI values (2.18 and 2.02), indicating greater photosynthetic surface longevity. This corresponded to an improvement of approximately 60 % over the absolute control T_{12} (1.33 and 1.13). Treatments T_5 (75 % RDF + two NUP sprays) and T_{11} (100 % RDF alone) remained statistically comparable to T_1 across both seasons, whereas T_{12} consistently recorded the lowest LAI values.

Table 4. Effect of foliar NUP and fertilizer regimes on plant height (cm) of finger millet at various growth stages

Treatments	30 DAT		60 DAT		90 DAT		Harvest	
	Summer	Rabi	Summer	Rabi	Summer	Rabi	Summer	Rabi
T_1 – 100 % RDF + 1 spray of NUP @ 0.75 % during tillering	49.0	44.2	75.9	73.6	114.8	110.9	136.9	131.7
T_2 – 75 % RDF alone	34.4	32.7	68.5	62.7	98.4	95.1	122.6	114.8
T_3 – 75 % RDF + 1 spray of NUP @ 0.75 % during tillering	39.4	36.2	71.7	66.5	105.8	99.8	128.3	123.9
T_4 – 75 % RDF + 1 spray of NUP @ 0.75 % during panicle-initiation (PI)	37.6	35.4	70.5	65.3	101.2	97.1	127.2	123.1
T_5 – 75 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	45.1	42.4	73.8	69.7	111.2	107.6	133.1	127.2
T_6 – 50 % RDF alone	30.1	28.5	63.1	58.3	93.5	92.8	105.7	101.5
T_7 – 50 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	33.2	30.9	67.5	61.2	95.6	93.9	120.8	110.3
T_8 – 100 % organic on 'N' equivalent + 1 sprays of NUP @ 0.75 % during tillering	35.7	33.8	69.0	63.6	99.9	95.2	124.8	119.4
T_9 – 75 % organic on 'N' equivalent + 2 sprays of NUP @ 0.75 % during tillering and PI stages	30.4	29.3	66.3	60.4	94.7	93.2	118.9	108.9
T_{10} – 50 % organic on 'N' equivalent + 2 sprays of NUP @ 0.75 % during tillering and PI stages	28.4	25.3	61.9	56.4	92.2	91.8	105.7	100.3
T_{11} – Control (100 % RDF alone)	43.9	40.5	72.1	67.9	109.8	102.7	129.1	125.5
T_{12} – Absolute control	25.1	22.9	57.9	54.1	90.7	87.9	101.2	99.5
SEd	1.96	1.83	3.85	4.04	5.31	5.69	8.13	7.12
CD (p=0.05)	4.07	3.80	7.99	8.38	11.0	11.8	16.8	14.7

Table 5. LAI of finger millet as influenced by foliar NUP and nitrogen management at different growth stages

Treatments	30 DAT		60 DAT		90 DAT		Harvest	
	Summer	Rabi	Summer	Rabi	Summer	Rabi	Summer	Rabi
T_1 – 100 % RDF + 1 spray of NUP @ 0.75 % during tillering	1.78	0.91	2.42	2.31	3.94	3.80	2.18	2.02
T_2 – 75 % RDF alone	0.72	0.51	1.81	1.62	3.50	3.19	1.82	1.67
T_3 – 75 % RDF + 1 spray of NUP @ 0.75 % during tillering	1.12	0.73	2.21	2.18	3.84	3.56	2.05	1.89
T_4 – 75 % RDF + 1 spray of NUP @ 0.75 % during panicle-initiation (PI)	0.97	0.69	2.14	2.12	3.73	3.43	2.01	1.84
T_5 – 75 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	1.33	0.82	2.37	2.25	3.87	3.75	2.10	1.95
T_6 – 50 % RDF alone	0.53	0.34	1.31	1.12	2.77	2.58	1.65	1.53
T_7 – 50 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	0.71	0.43	1.64	1.54	3.09	2.99	1.86	1.73
T_8 – 100 % organic on 'N' equivalent + 1 sprays of NUP @ 0.75 % during tillering	0.81	0.56	1.92	1.82	3.61	3.29	1.97	1.79
T_9 – 75 % organic on 'N' equivalent + 2 sprays of NUP @ 0.75 % during tillering and PI stages	0.54	0.41	1.53	1.21	3.02	2.73	1.78	1.62
T_{10} – 50 % organic on 'N' equivalent + 2 sprays of NUP @ 0.75 % during tillering and PI stages	0.44	0.23	1.11	0.93	2.61	2.37	1.61	1.50
T_{11} – Control (100 % RDF alone)	1.28	0.79	2.32	2.20	3.86	3.67	2.08	1.92
T_{12} – Absolute control	0.21	0.15	0.91	0.74	1.87	1.63	1.33	1.13
SEd	0.04	0.04	0.10	0.07	0.16	0.18	0.11	011
CD (p=0.05)	0.09	0.08	0.22	0.15	0.33	0.39	0.24	0.23

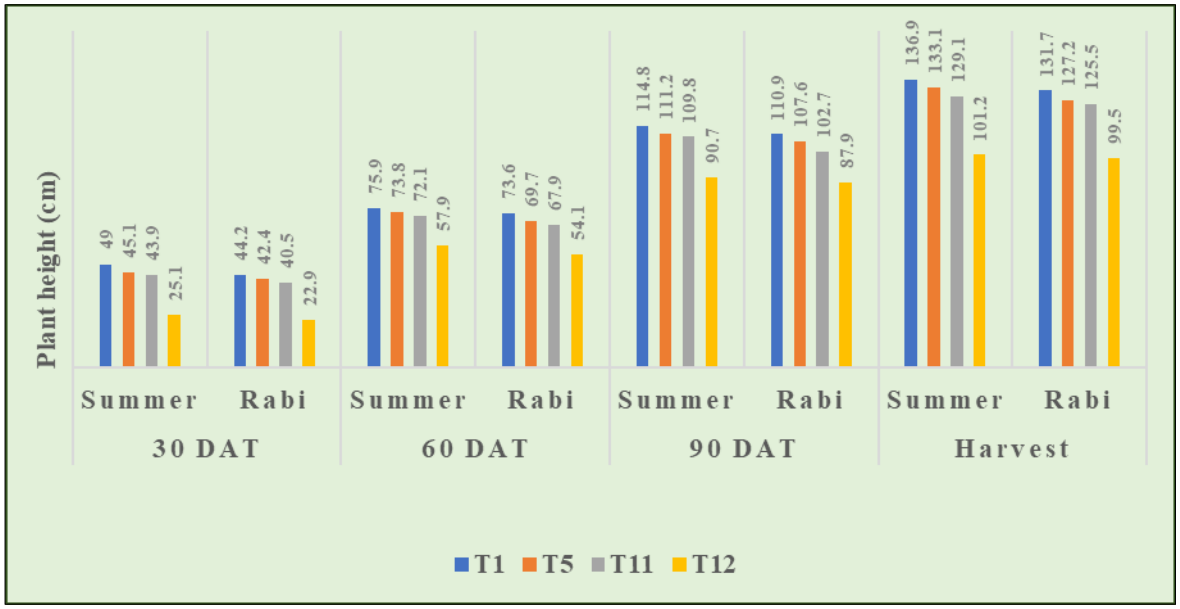

Fig. 1. Effect of nano urea and nitrogen regimes on plant height of finger millet during summer and rabi 2024.

Normalized difference vegetation index (NDVI)

Across all growth stages (Fig. 2), T_1 (100 % RDF + one NUP spray at tillering) consistently recorded higher NDVI values (0.41, 0.76 and 0.85 during summer and 0.38, 0.75 and 0.83 during rabi at 30, 60 and 90 DAT respectively). Treatments T_5 (75 % RDF + two NUP sprays) and T_{11} (100 % RDF alone) remained statistically comparable to T_1 across both seasons, indicating that foliar application of NUP was effective in sustaining canopy greenness and nitrogen use efficiency even under reduced RDF levels.

Crop growth indices

The CGR increased with crop age, peaking between 60–90 DAT and declining thereafter (Table 6). Treatment T_1 (100 % RDF + one NUP spray at tillering) showed the highest CGR (5.39 and 5.05 g m^2 day^{-1} during summer and rabi respectively), about double that of the control. Enhanced CGR under NUP treatments indicates greater biomass accumulation due to improved nitrogen availability and sustained photosynthetic activity. RGR followed the typical declining trend with crop age, showing no significant variation

Table 6. Crop growth indices (CGR, RGR and AGR) of finger millet under varying nitrogen and nano urea treatments during summer and rabi 2024

CGR

Treatments	30–60 DAT		60–90 DAT		90– DAT Harvest	
	Summer	Rabi	Summer	Rabi	Summer	Rabi
T_1 – 100 % RDF + 1 spray of NUP @ 0.75 % during tillering	4.54	4.11	5.39	5.05	4.84	4.48
T_5 – 75 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	4.44	3.84	4.67	4.76	4.27	3.98
T_{11} – Control (100 % RDF alone)	4.25	3.36	4.61	5.12	3.21	3.07
T_{12} – Absolute control	2.32	1.92	2.42	2.38	1.39	1.33
SEd	0.15	0.17	0.61	0.15	0.83	0.45
CD (*p*=0.05)	0.32	0.36	1.28	0.31	1.73	0.93

RGR

Treatments	30–60 DAT		60–90 DAT		90– DAT Harvest	
	Summer	Rabi	Summer	Rabi	Summer	Rabi
T_1 – 100 % RDF + 1 spray of NUP @ 0.75 % during tillering	0.0436	0.0416	0.0208	0.0209	0.0139	0.0137
T_5 – 75 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	0.0441	0.0407	0.0189	0.0209	0.0135	0.0131
T_{11} – Control (100 % RDF alone)	0.0448	0.0391	0.0195	0.0240	0.0105	0.0106
T_{12} – Absolute control	0.0416	0.0396	0.0184	0.0207	0.0081	0.0091
SEd	0.0021	0.0027	0.0033	0.0019	0.0013	0.0015
CD (*p*=0.05)	NS	NS	NS	NS	0.0027	NS

AGR

Treatments	30–60 DAT		60–90 DAT		90– DAT Harvest	
	Summer	Rabi	Summer	Rabi	Summer	Rabi
T_1 – 100 % RDF + 1 spray of NUP @ 0.75 % during tillering	45.44	41.10	53.86	50.45	48.41	44.85
T_5 – 75 % RDF + 2 sprays of NUP @ 0.75 % during tillering and PI stages	44.39	38.38	46.69	47.56	42.74	39.83
T_{11} – Control (100 % RDF alone)	42.50	33.58	46.14	51.20	32.09	30.74
T_{12} – Absolute control	23.20	19.24	24.24	23.81	13.94	13.27
SEd	1.58	1.77	1.80	2.49	2.30	1.37
CD (*p*=0.05)	3.27	3.68	3.74	5.17	4.77	2.84

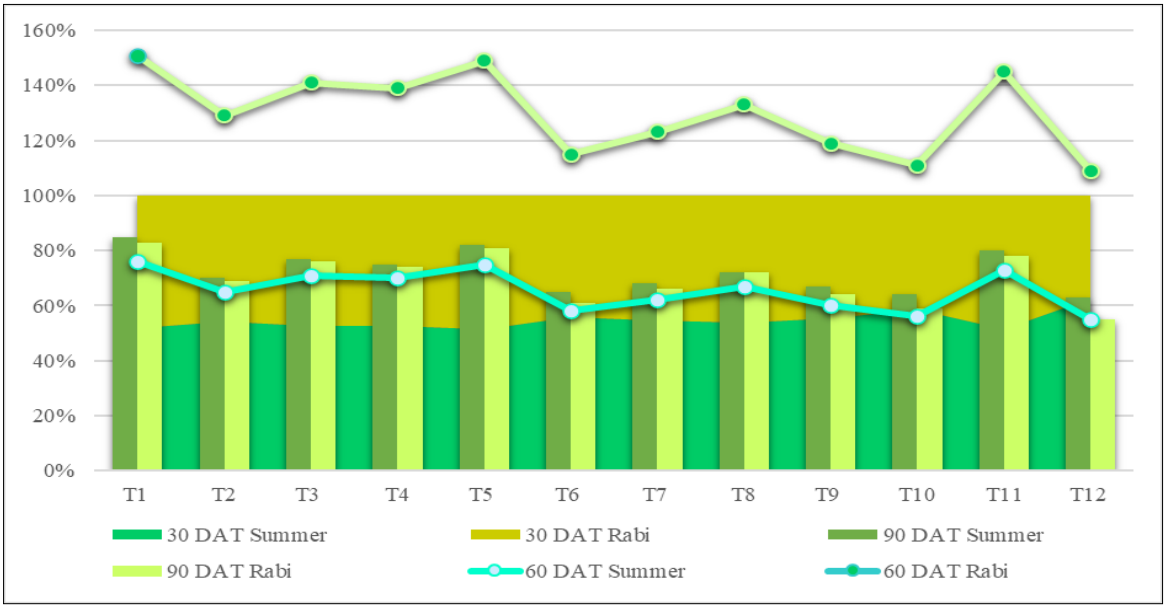

Fig. 2. Effect of NUP and varying nitrogen levels on NDVI of transplanted finger millet (summer and rabi 2024).

among treatments at early stages. However, at the 90 DAT–harvest phase, T_1 recorded the highest RGR (0.0139 g g^{-1} day^{-1}), significantly higher than the organic and control treatments. Similarly, AGR exhibited a sigmoidal pattern, peaking between 60–90 DAT. Treatments T_1 and T_5 maintained higher AGR (>45 g day^{-1}), reflecting efficient conversion of assimilates into biomass through improved nitrogen uptake from foliar NUP application.

Comparative physiological profiling using hierarchical clustering

Hierarchical clustering of normalized physiological indices (Fig. 3) clearly differentiated the treatments into high-, moderate- and low -performance groups. Treatments T_1 and T_5 clustered together, reflecting their consistent superiority across LAI, NDVI, CGR and AGR, while T_{12} formed a distinct low-performance cluster. This multivariate visualization confirmed the integrated effect of soil-applied RDF and foliar NUP in enhancing physiological efficiency.

Yield

Grain yield varied significantly with nutrient management (Fig. 4). The highest yield was obtained under T_1 (100 % RDF + one NUP spray at tillering) with 2.59 t ha^{-1} (summer) and 2.56 t ha^{-1} (rabi), statistically similar to T_5 (75 % RDF + two NUP sprays) and T_{11} (100 % RDF). These treatments outperformed the absolute control by nearly 48–50 %, indicating that reduced RDF (75 %) supplemented with NUP can achieve yields comparable to the full fertilizer dose. Treatments receiving only organic N or reduced RDF without NUP showed lower productivity, underscoring the synergistic role of foliar nano urea in sustaining yield.

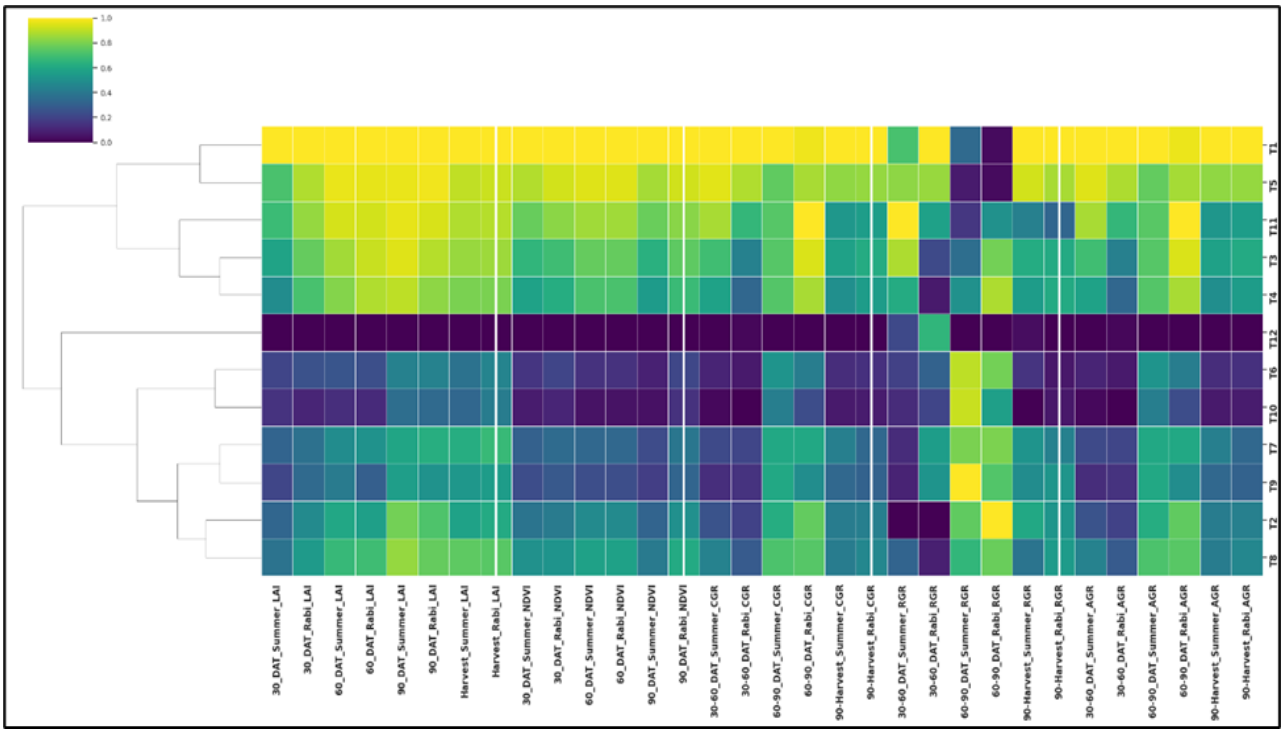

Fig. 3. Hierarchical clustering of physiological parameters (LAI, NDVI, CGR, RGR and AGR) of finger millet under different treatments using Ward's method based on Euclidean distance.

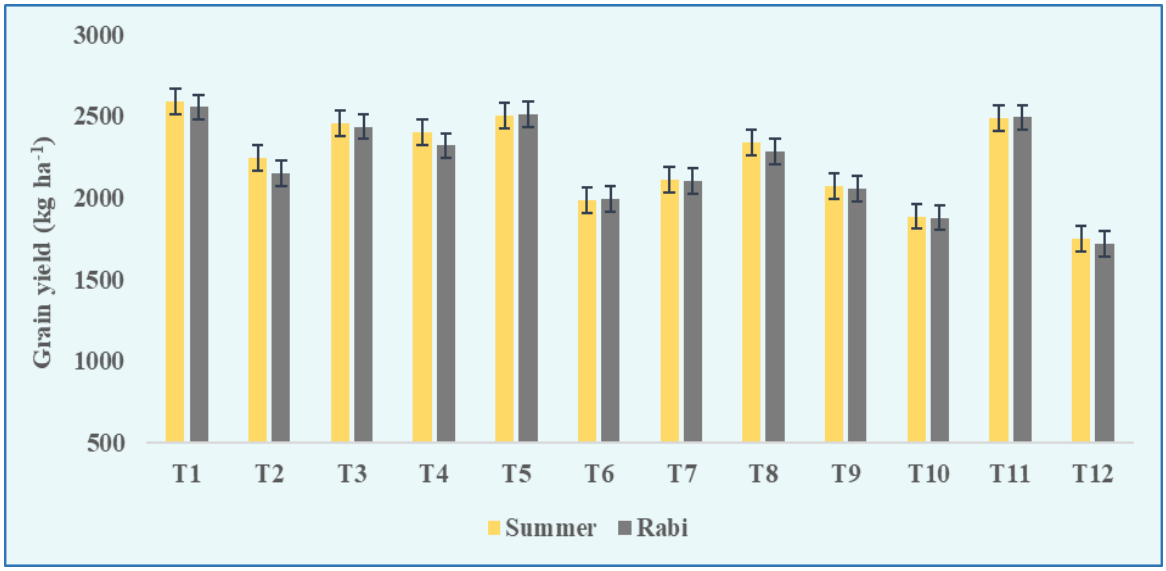

Fig. 4. Grain yield of finger millet as affected by foliar NUP and nitrogen management during summer and rabi 2024 (bars = mean ± SE).

Discussion

Growth parameter

Conventional urea applied as a foliar spray dissolves on the leaf surface and enters primarily through cuticular diffusion or hydrated stomata; however, this pathway is inherently slow and inefficient. A substantial proportion of the applied urea recrystallizes upon drying, making it highly vulnerable to wash-off, volatilization and deposition losses, which considerably restricts its effective absorption. As a result, foliar urea often produces only a short-lived spike in nitrogen availability, leading to temporary canopy greening followed by a rapid decline in metabolic activity once the nitrogen is depleted (33, 34).

In contrast, the significant increase in plant height observed under T_1 (100 % RDF + one NUP spray at tillering) and T_5 (75 % RDF + two sprays) indicates the effectiveness of foliar nano-nitrogen in sustaining vegetative growth. Nano urea contains nanoscale nitrogen particles that readily penetrate stomatal openings and cuticular microchannels, enabling rapid absorption and direct entry into mesophyll tissues (35). Notably, T_5 produced grain yields statistically comparable to the full 100 % RDF, demonstrating that nano urea can effectively compensate for a 25 % reduction in soil-applied nitrogen. Economically, this reduction lowers fertilizer costs and increases profitability for farmers, while environmentally, it helps reduce nitrate leaching, nitrous oxide emissions and soil acidification-major concerns associated with excessive nitrogen use (36). These benefits align strongly with the SDG, particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

Once internalized, nitrogen becomes readily available for amino acid synthesis, protein formation and cell division, processes that directly support internode elongation and biomass accumulation (37). Nano urea also enhances the activity of key nitrogen assimilation enzymes such as nitrate reductase and glutamine synthetase, thereby improving nitrogen metabolism and promoting vegetative vigour (38). Because nano formulations minimize volatilization losses and provide a controlled and sustained release of nitrogen, plants experience a steadier supply of available nitrogen, unlike the rapid peaks and declines characteristic of conventional foliar urea. Similar improvements in plant height following nano-nitrogen foliar feeding have been reported in maize, wheat and rice (39–41). The enhanced vegetative growth in NUP treatments may therefore be attributed to improved nitrogen translocation efficiency and sustained leaf metabolic activity.

The weaker performance of the organic treatments (T_8, T_9 and T_{10}) is mainly due to the slow mineralization of nutrients in FYM, which releases nitrogen too gradually to meet the rapid early-season demand of finger millet. Because nitrogen remains in complex organic forms for longer, plants receive insufficient N during critical growth stages, resulting in lower chlorophyll content and weaker canopy development. Organic sources also provide far less immediately available nitrogen than nano urea (42).

Physiological parameters

Higher LAI and NDVI values under NUP treatments, particularly in T_1 and T_5, indicate an improved canopy structure and enhanced photosynthetic efficiency. Nitrogen is a primary component of chlorophyll, proteins and enzymes involved in carbon fixation (43). When nitrogen is readily available through nano urea, leaf expansion is accelerated and chlorophyll density increases, resulting in broader and more functional leaves (44). Since LAI strongly determines light interception, a higher LAI enhances daily photosynthetic carbon gain, contributing to better growth and yield formation (45).

NDVI is highly sensitive to changes in leaf nitrogen because N is tightly linked to RUBISCO content, the enzyme responsible for CO_2 fixation in the Calvin cycle (46). Enhanced nitrogen availability through nano-urea increases RUBISCO synthesis, leading to improved photosynthetic rate, higher carbon assimilation and stronger canopy vigour (47, 48). This explains why T_1 and T_5 maintained consistently higher NDVI values across stages. Additionally, nano-nitrogen minimizes N losses through volatilization or leaching, allowing more nitrogen to be used for chlorophyll synthesis and maintenance (49). As a result, enhanced LAI and NDVI together contribute to higher CGR, RGR and AGR, indicating greater biomass accumulation and sustained physiological activity.

The enhanced CGR, RGR and AGR in NUP-supplemented treatments reflect improved nitrogen assimilation and biomass

production. The T_1 treatment achieved nearly twice the CGR of the control during the 60–90 DAT period, indicating sustained vegetative growth under optimal nitrogen availability. The CGR, RGR and AGR under nano urea treatments primarily reflect improved nitrogen assimilation efficiency. Foliar-applied nano urea reaches the photosynthetically active tissues directly, improving chlorophyll formation, enzyme activation and carbohydrate synthesis (50). NUP ensures a more uniform nitrogen supply throughout critical stages, leading to higher leaf metabolic activity, broader canopy structure and greater dry matter accumulation (51). These physiological improvements translate into significantly higher growth rates compared with the untreated control.

Grain yield

The marked increase in grain yield under T_1 (2.6 t ha^{-1}) and T_5 (2.5 t ha^{-1}) treatments, which were approximately 50 % higher than the control, can be attributed to enhanced nitrogen assimilation and assimilate translocation to reproductive organs. Improved NDVI and LAI earlier in the season lead to greater assimilate production, which is subsequently partitioned toward panicle development and grain filling. Nano urea improves nitrogen use efficiency, maintains higher chlorophyll content and supports prolonged photosynthetic activity, ensuring better assimilate translocation to reproductive sinks (52). These findings are consistent with reports in cereal crops where nano-nitrogen application improved spikelet fertility, reduced sterility and enhanced grain yield by increasing nutrient availability at critical stages (53). The superior performance of T_1 and T_5 across both seasons confirms that integrating soil-applied nitrogen with foliar nano urea is an effective strategy for improving productivity in finger millet systems.

Conclusion

The foliar application of NUP in combination with graded recommended fertilizer doses significantly improved growth, canopy physiology and grain yield of finger millet compared with conventional nutrient management. Among treatments, 100 % RDF + one NUP spray at tillering (T_1) consistently recorded the highest growth and yield attributes during both summer and rabi seasons. Its performance was statistically comparable to 75 % RDF + two NUP sprays (T_5) and 100 % RDF alone (T_{11}), demonstrating that nano urea supplementation can partially substitute for soil-applied nitrogen without yield loss. This highlights the potential of nano urea to enhance fertilizer-use efficiency and reduce total nitrogen requirement by up to 25 %. Overall, integrating foliar nano urea with recommended or reduced fertilizer regimes enhanced vegetative growth, biomass accumulation and assimilate partitioning, leading to higher yield and nitrogen-use efficiency in finger millet. The results underscore nano urea's role as a sustainable nutrient management tool, capable of reducing nitrogen inputs while maintaining productivity. Further field-scale and multi-location studies are warranted to evaluate its long-term effects on soil fertility and system sustainability.

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Authors' contributions

AK conducted the field trials, performed data curation and formal analysis and prepared the original draft of the manuscript. TK was responsible for conceptualization, validation, provision of resources, supervision and manuscript review and editing. MV contributed to investigation, validation and manuscript review and editing. KP contributed to conceptualization, project administration, validation, visualization, provision of resources, supervision and manuscript review and editing. DR, VD^1, MG and HVP contributed to manuscript review and editing. VS was involved in conceptualization, methodology, data curation, investigation and manuscript review and editing. VD^2 contributed to visualization, provision of resources and manuscript review and editing. [VD^1- Vanathi Durai; VD^2- Vijayalakshmi Dhashnamurthi].

Compliance with ethical standards

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Ethical issues: None

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