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# Evaluating the nitrogen substitution potential of nano-urea for improving growth kinetics, yield attributes and productivity of maize in acidic soils

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## Abstract

Nitrogen (N) management remains a critical agronomic challenge due to various losses such as leaching and volatilisation which necessitate more efficient delivery mechanisms especially in acidic soils. This study investigated the N substitution potential of nano-urea in maize (*Zea mays* L.) cultivated under acidic soil conditions. A field experiment was conducted using a randomised complete block design with 12 treatments which compared varying levels 0 %, 50 %, 75 % and 100 % of the recommended dose of nitrogen (RDN) applied either alone or in combination with foliar sprays of nano-urea or 2 % conventional prilled urea solution. Growth kinetics revealed that the combined application of 100 % RDN with nano-urea consistently maximised crop growth rate, net assimilation rate and leaf area duration. Importantly, reducing the basal N dose to 75 % RDN while supplementing with foliar nano-urea produced physiological responses and grain yield (5.79 t $ha^{-1}$) which was statistically comparable to the 100 % RDN (6.24 t $ha^{-1}$). This demonstrates a 25 % RDN substitution without incurring agronomic penalties. Furthermore, this 25 % N substitution approach optimised nitrogen use efficiency (NUE); the agronomic efficiency (AE) and apparent recovery efficiency (RE) of the 75 % RDN plus nano-urea treatment remained statistically comparable to the 100 % RDN. Pearson's correlation analysis confirms that the enhancement of growth kinetics through nano-urea directly translated into improved sink capacity and final grain yield. In contrast, conventional 2 % prilled urea sprays showed high variability and failed to provide statistically at par results. Economic analysis indicated that the 75 % RDN plus nano-urea strategy maintained net returns and a benefit-cost (B:C) ratio statistically at par to the 100 % RDN. These findings suggest that integrating foliar nano-urea with reduced N applications represents an efficient and sustainable nutrient management strategy for maize in acidic soils, reducing the economic burden and environmental footprint of excessive soil N applications while sustaining overall profitability.

**Keywords:** acid soils; maize growth kinetics; nano-urea; nitrogen substitution; yield attributes

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## 1. Introduction

Maize (*Zea mays* L.) is one of the most important cereals worldwide which contributes to global food security of an increasing population and it is crucial for industrial and secondary agriculture. Realisation of its vast genetic yield potential is largely contingent upon the intensive application of chemical fertilisers especially nitrogen (N) which serves as the most critical nutrient regulating vegetative growth, photosynthetic efficiency and sink development (1). However, the global dependence on conventional soil-applied nitrogen practices predominantly in the form of broadcasted prilled urea has led to significant economic and environmental constraints. Furthermore, conventional broadcasting often leads to inefficient utilisation of fertilisers; therefore, adopting precise nutrient delivery systems is essential for improving maize productivity and maximising nitrogen recovery. Nitrogen use efficiency (NUE) in cereal production remains low and seldom exceeds 30–40 % indicating that the majority of applied nitrogen is lost to the environment rather than assimilated into economic yield (2).

These losses and inefficiencies are intensified in acidic soil conditions. In low pH soils, conventional basal urea undergoes rapid hydrolysis to ammonium, which may subsequently be converted to nitrate through

nitrification. The resulting nitrate is susceptible to leaching beyond the active root zone, while nitrogen losses may also occur through ammonia ($NH_3$) volatilisation. These processes are strongly influenced by the soil's pH buffering capacity (3). In addition, the inherent chemical imbalances of acid soils particularly aluminum ($Al^{3+}$) toxicity severely constrains root proliferation and development thereby limiting the crop's capacity to forage and the final assimilation of nitrogen during peak vegetative demand (4). As a consequence, farmers are often compelled to apply excessive quantities of urea to avoid these losses which initiate an unsustainable cycle of increasing input costs, water contamination and degradation of soil health.

Foliar feeding has emerged as a viable supplementary strategy to overcome nutrient unavailability and leaching constraints in problematic (acid) soils. Conventional 2 % prilled urea sprays have been employed to bypass soil limitations. However, their effectiveness is often constrained by slow cuticular penetration, significant volatilisation from leaf surface and risk of localised phytotoxicity or micro-osmotic stress (5). Recently, nanotechnology has introduced a transformative alternative. Nano-urea is characterised by nano-scale size (typically 20–50 nm) and a higher surface area-to-volume ratio which fundamentally modify the dynamics of foliar assimilation. These nano-scale particles (nano-urea) enable rapid and efficient penetration through stomatal and epidermal pathways ultimately facilitating accelerated intracellular nitrogen metabolism without the physiological stress commonly associated with conventional fertilisers (6).

While recent field trials have highlighted its potential and climate resilience benefits of nano-fertilisers in cereal systems (7), there remains a need for comprehensive and quantitatively rigorous data showing their precise substitution capacity under intentional basal nitrogen deficits. In particular, the effects of replacing soil applied urea with foliar nano-urea on key physiological growth kinetics namely crop growth rate, net assimilation rate and leaf area duration have not been adequately characterised within acidic soil ecosystems. To address this research gap, the present study was designed with the primary objective of evaluating the nitrogen substitution capacity of foliar nano-urea in maize cultivated under acid soil conditions. This research evaluates compensatory source-sink dynamics, derived growth kinetics, yield attributes productivity and profitability, thereby determining whether foliar nano-urea nutrition can effectively mitigate the physiological constraints associated with reduced nitrogen applications.

## 2. Materials and Methods

### Experimental site and soil characteristics

A field experiment was conducted during the kharif season of 2022 at the ICAR-Indian Agricultural Research Institute, Jharkhand, India which is located at 24°16' N and 85°21' E with an elevation of 413 m above mean sea level. The meteorological data during the kharif season (standard meteorological weeks 28–45, July–November, 2022) indicated a stable thermal regime with maximum temperatures ranging between 26 and 31 °C and minimum temperatures gradually declining from 20 °C to 10 °C toward harvesting period (Fig. 1). Precipitation was concentrated during the active vegetative and early reproductive phases (Standard meteorological week (SMW) 28–40) with a peak observed at SMW 34, which sustained a high maximum relative humidity (> 80 %). During the late grain-filling and maturity stages (SMW 41–45) rainfall mostly ceased and daily sunshine duration peaked at approximately 9 hr/day, which provided optimal dry conditions for crop maturation.

The experimental field was characterised by a well-drained and acidic soil profile. Soil samples were collected from a depth of 0–15 cm before sowing and fertiliser application from a representative plot. The soil texture was sandy loam with a bulk density of 1.69 megagram (Mg) $m^{-3}$. Chemical analysis indicated an acidic pH of 6.3, organic carbon content of 0.27 %, low available nitrogen 147 kg $ha^{-1}$, low available phosphorus 8.2 kg $ha^{-1}$ and medium available potassium 136 kg $ha^{-1}$.

### Experimental design and treatment details

The experiment was conducted using a randomised complete block design comprising 12 different nitrogen management treatments and each replicated 3 times. The plot dimensions were 5 × 4.8 $m^2$, providing a total gross area of 24 $m^2$ per plot. The treatments were formulated to evaluate the substitution capacity of foliar applied nano-urea and conventional prilled urea under varying levels of the recommended dose of nitrogen (RDN). The detailed treatment structure is presented in Fig. 2. The 12 treatments consisted of nitrogen applied at 0 %, 50 %, 75 % and 100 % of RDN, either alone or in combination with foliar sprays of nano-urea or 2 % prilled urea spray. This arrangement enabled direct comparison between conventional applied nitrogen practices and foliar supplementation strategies thereby facilitating quantification of the compensatory potential of nano-urea under reduced nitrogen conditions. The recommended dose of fertiliser for the region was 150 : 75 : 50 kg nitrogen : phosphorus pentoxide : potassium oxide (N : $P_2O_5$ : $K_2O$) $ha^{-1}$. A uniform basal dose of the full phosphorus and potassium was applied to all plots while nitrogen was applied according to the specific treatment protocols. For foliar treatments, nano-urea (Indian Farmers Fertiliser Cooperative Limited (IFFCO), 4 % N weight/volume (w/v)) was applied at a rate of 4 mL $L^{-1}$ with a spray volume of 450 L $ha^{-1}$, whereas conventional urea was applied as a 2 % solution by the addition of urea fertiliser in water (w/v) (20 g $L^{-1}$). Foliar sprays were administered uniformly using a knapsack sprayer at critical stages, specifically 32 and 50 days after sowing (DAS) to maximise stomatal assimilation (6). No adjuvants or surfactants were added to the foliar spray solutions.

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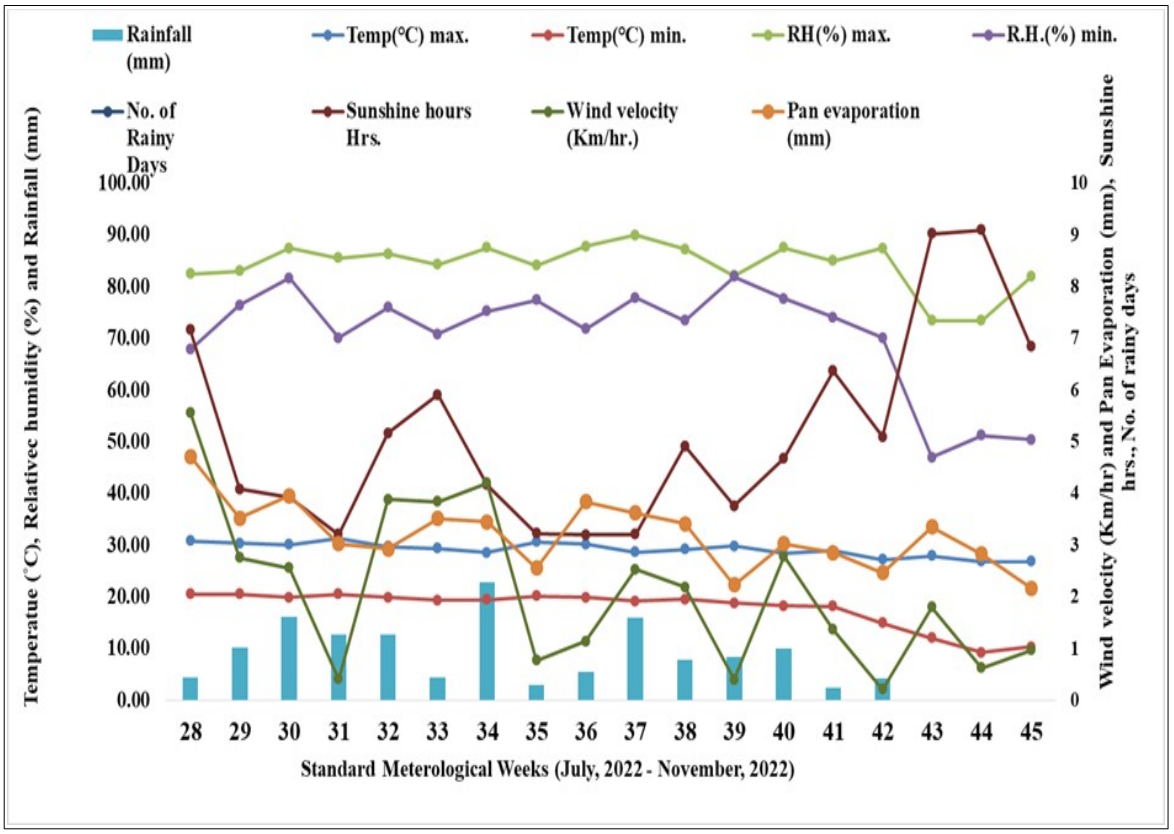



**Fig. 1**. Standard meteorological weeks 2022 weather data of maize cropping system during field experiments.

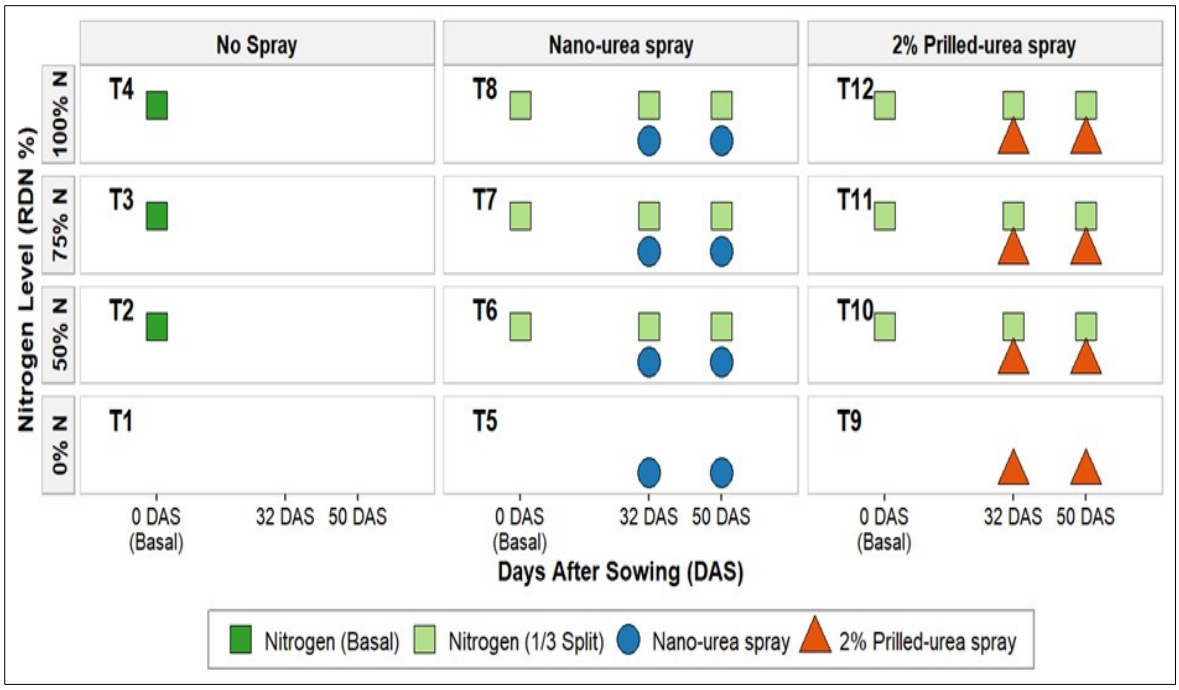



**Fig. 2.** Comprehensive treatment details of the experiment.

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## Crop establishment

The maize hybrid DMH-121 was sown on July 19th, 2022 using spacing of 60 × 20 cm. Appropriate agronomic practices were maintained uniformly across all plots i.e. appropriate irrigation scheduling (two irrigations applied during the crop's dry spell), weed management (hand weeding and spray of atrazine and tembotrione) and pest management (spray of the insecticide chlorantraniliprole 18.5 % suspension concentrate (SC)).

## Observations and measurements

### Physiological growth kinetics

Destructive plant sampling was performed at 40 and 80 days after sowing (DAS). Plant dry weight ($W$) and leaf area (L) were recorded at time one ($t_1$) 40 DAS and time two ($t_2$) 80 DAS. To clarify the sampling methodology per plot, 5 randomly selected plants were utilised for non-destructive plant height measurements, 3 for leaf area index (LAI) estimations and 2 for destructive dry matter accumulation. The derived physiological growth indices were calculated using standard formulas (8, 9).

Crop growth rate (CGR): $CGR = \frac{W_2 - W_1}{p * (t_2 - t_1)}$ g m$^{-2}$ day$^{-1}$

Relative growth rate (RGR):

$$RGR = \frac{\ln W_2 - \ln W_1}{t_2 - t_1} \text{ g g}^{-1} \text{ day}^{-1}$$

Net assimilation rate (NAR):

$$NAR = \frac{(W_2 - W_1) * (\ln(L_2) - \ln(L_1))}{(t_2 - t_1) * (L_2 - L_1)} \text{ g m}^{-2} \text{ day}^{-1}.$$

Leaf area duration (LAD):

$$LAD = \left(\frac{L_1 + L_2}{2}\right) * (t_2 - t_1) \text{ days}$$

Where, $W_1$ and $W_2$ represent the total plant dry weight (g) at times $t_1$ and $t_2$ respectively. $L_1$ and $L_2$ denote the leaf area per plant (m²). *p* denotes the ground area (m²) occupied by the plant and (ln) indicates the natural logarithm.

### Yield attributes and productivity

The representative plants were randomly selected from the net plot area of each treatment to record yield attributes, including cob length, cob girth, number of rows per cob and grains per row at physiological maturity. The cobs harvested from the net plot were sun dried and threshed to determine grain yield and stover yield. These values were subsequently converted to tonnes per hectare (t ha$^{-1}$) at a standard moisture content of 15 %.

### Nitrogen use efficiency and economic analysis

Nitrogen concentration in grain and stover was measured using the modified micro-Kjeldahl method. Total nitrogen uptake (kg ha$^{-1}$) was calculated by multiplying nitrogen concentration with the corresponding dry matter yield. To assess the effect of foliar urea application, two efficiency indices were used:

**Agronomic efficiency (AE):**

$$AE = \frac{Y - Y_0}{F}$$

**Apparent recovery efficiency (RE):**

$$\text{RE} = \frac{U - U_0}{F} \times 100$$

Where:

$Y$ = grain yield of fertilised plots (kg ha$^{-1}$)

$Y_0$ = grain yield of unfertilised control (kg ha$^{-1}$)

$F$ = nitrogen applied (kg ha$^{-1}$)

$U$ = total nitrogen uptake in fertilised plots (kg ha$^{-1}$)

$U_0$ = total nitrogen uptake in control plots (kg ha$^{-1}$)

### Economic analysis

Cost of cultivation (₹ ha$^{-1}$): Calculated by including all variable inputs such as tillage, seed, basal fertilisers, foliar sprays and labour, based on local market rates.

Gross returns (₹ ha$^{-1}$): Estimated using the Minimum Support Price (MSP) and local market prices stover.

Net returns (₹ ha$^{-1}$):

$$Net\ Returns = Gross\ Returns - Cost\ of\ Cultivation$$

Benefit-cost ratio (B:C):

$$B:C\ Ratio = \frac{Net\ Returns}{Cost\ of\ Cultivation}$$

## Statistical analysis and data visualisation

The primary dataset was subjected to analysis of variance (ANOVA) appropriate for a randomised complete block design (10). Treatment effects were tested for statistical significance at 5 % probability level ($p < 0.05$). All advanced statistical computations and visualisations were performed using the R programming (11). Derived growth kinetics were represented through grouped bar plots generated with the *ggplot2* package (12). Interrelationships among yield attributes were quantified using Pearson's correlation matrix (13). In addition, the variance and distribution of yield parameters were visualised using faceted box and whisker plots to illustrate data density and interquartile ranges across all nitrogen management strategies.

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## 3. Results and Discussion

### Growth kinetics

The grouped bar chart of the derived growth indices (Fig. 3) illustrates the potential of foliar nano-urea sprays (NUS) across varying basal nitrogen levels. The absolute control ($T_1$) exhibited a restricted overall assimilatory capacity, recording the lowest crop growth rate (CGR; 1.96 g $m^{-2}$ $day^{-1}$) and leaf area duration (LAD; 48.67 days). While $T_1$ displayed a higher net assimilation rate (NAR; 1.61 g $m^{-2}$ $day^{-1}$) and relative growth rate (RGR; 0.045 g $g^{-1}$ $day^{-1}$) due to minimal mutual leaf shading prior to canopy closure, its overall physiological footprint remained constrained. In contrast, the application of 100 % basal nitrogen combined with two foliar nano-urea sprays ($T_8$) supported significant canopy longevity, achieving the highest LAD (182.00 days) among all treatments. This indicates that targeted foliar delivery helped delay early leaf senescence and sustained photosynthetic activity under the experimental conditions (1).

Furthermore, the visual trends clarify the mechanism underlying the nitrogen substitution effect. The standard agronomic practice of 100 % basal nitrogen ($T_4$) established a baseline physiological response, achieving a CGR of 2.84 g $m^{-2}$ $day^{-1}$ and a LAD of 149.67 days. However, reducing the basal soil dose to 75 % and supplementing with two foliar nano-urea sprays ($T_7$) produced a kinetic profile that closely mirrored and even slightly exceeded this baseline in key metrics (CGR: 3.08 g $m^{-2}$ $day^{-1}$; LAD: 155.27 days). This demonstrates that a 25 % reduction in basal nitrogen, when supplemented with nano-urea, did not impose a physiological penalty (14). Such substitution approaches are particularly relevant in acid soils, where soil-applied urea is susceptible to leaching and delayed mineralisation (3). The elevated LAD and sustained CGR observed in $T_7$ suggest that nano-urea particles were effectively assimilated through the stomata during peak vegetative demand, supporting the “stay-green” trait and maintaining photosynthetic efficiency by mitigating nutrient-availability issues common to acidic soils (15, 16).

To further evaluate physiological efficiency under nitrogen deficit conditions, a targeted comparison was drawn between the baseline standard ($T_4$: 100 % RDN), 25 % reduced N with nano-urea ($T_7$: 75 % RDN + NUS) and 25 % reduced N with conventional foliar urea ($T_{11}$: 75 % RDN + 2 % prilled urea spray). Although both $T_7$ and $T_{11}$ received the same 25 % reduction in soil nitrogen, their physiological responses diverged. The conventional 2 % prilled urea spray ($T_{11}$) was comparatively less effective in sustaining overall canopy longevity, exhibiting a lower LAD (134.40 days) than both the $T_4$ baseline (149.67 days) and the superior $T_7$ treatment (155.27 days).

The kinetic data indicates a more consistent physiological response with nano-urea over conventional foliar sprays. Even under full nitrogen supply, the prilled urea foliar treatment ($T_{12}$) demonstrated a robust physiological profile but did not reach the upper canopy thresholds attained by $T_8$ (LAD: 170.73 days vs. 182.00 days respectively). This difference in performance may be attributed to the higher surface area to volume ratio of nano-urea particles, which can facilitate stomatal penetration and intracellular utilisation (6). In contrast, conventional 2 % prilled urea sprays generally experience slower assimilation rates, potential volatilisation losses from the leaf surface and micro-osmotic stress (5), rendering them comparatively less effective in supporting crop canopy growth under N-deficient conditions.

### Yield attributes

Pearson correlation analysis was conducted to quantify the relationships between cob length, cob girth, rows per cob, grains per row, grains per cob, cob yield, 1000 grain weight, shelling percent and final grain yield across all nitrogen management practices (Fig. 4). The scatterplot matrix revealed a highly significant enhancement across yield attributes. Grain yield possessed the strongest positive correlation with total cob yield ($r$ = 0.932***), number of grains per cob ($r$ = 0.907***) and cob length ($r$ = 0.903***). These strong correlations indicate that physical sink expansion was the primary determinant of productivity in this trial and remains consistent with recent findings (17). Cob length has a substantial influence on grain site realisation showing strong positive correlations with the number of rows per cob ($r$ = 0.727***) and grains per row ($r$ = 0.751***). Interestingly, while 1000 grain weight was significantly correlated with final grain yield ($r$ = 0.637***), this relationship was weaker than that between grain number and yield ($r$ = 0.907***). This physiological hierarchy suggests that yield enhancement under optimal nitrogen management was driven primarily by the establishment and survival of a greater sink size rather than by kernel filling alone (18). The concurrent improvement in shelling percentage ($r$ = 0.730***) further confirms that efficient partitioning of dry matter to the economic sink was maintained alongside cob expansion. While the correlation matrix established the physiological pathways to higher yield, treatment wise performance revealed the specific efficiency of nano-urea applications, particularly under acidic soil conditions where nitrogen is highly susceptible to leaching and volatilisation (3). A critical observation from the kinetic and yield data was the compensatory action of foliar nano-fertiliser. When the basal nitrogen dose was reduced in $T_3$ (75 % RDN), the crop exhibited significant sink limitation compared to the standard $T_4$ (100 % RDN) practice, resulting in reduced cob length and increased kernel abortion at the cob tip due to late-season nitrogen deficiency.

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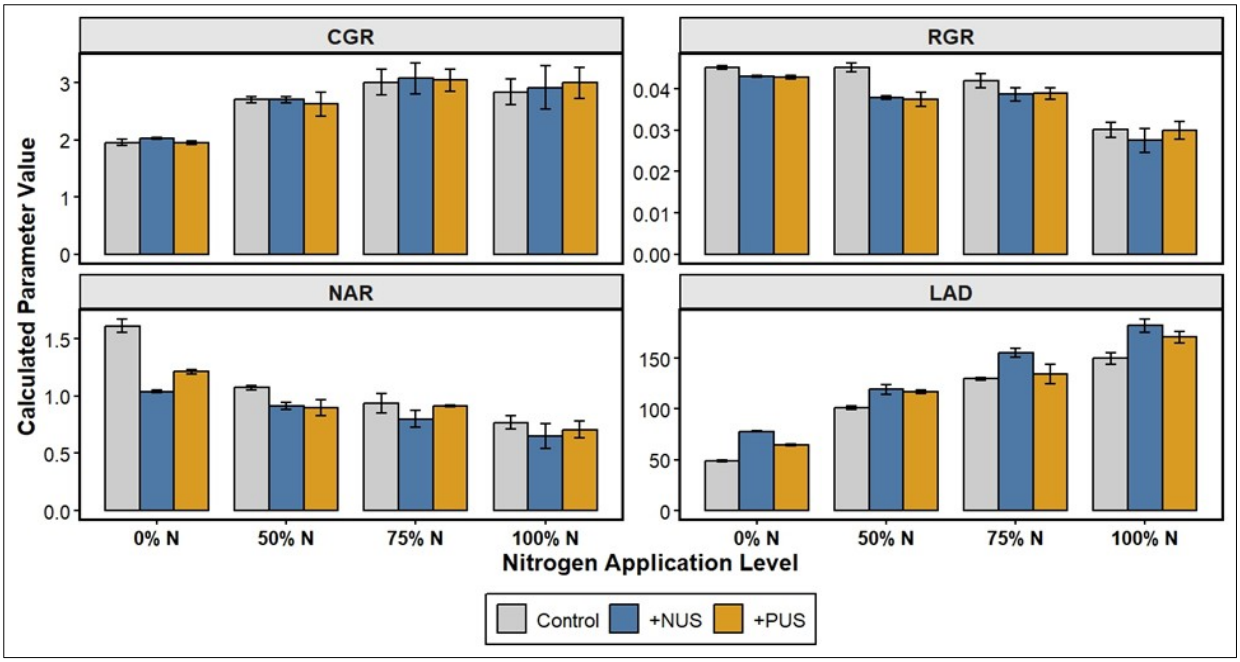



**Fig. 3.** Effect of varying basal nitrogen application levels and foliar urea supplementation on the physiological growth kinetics of maize.

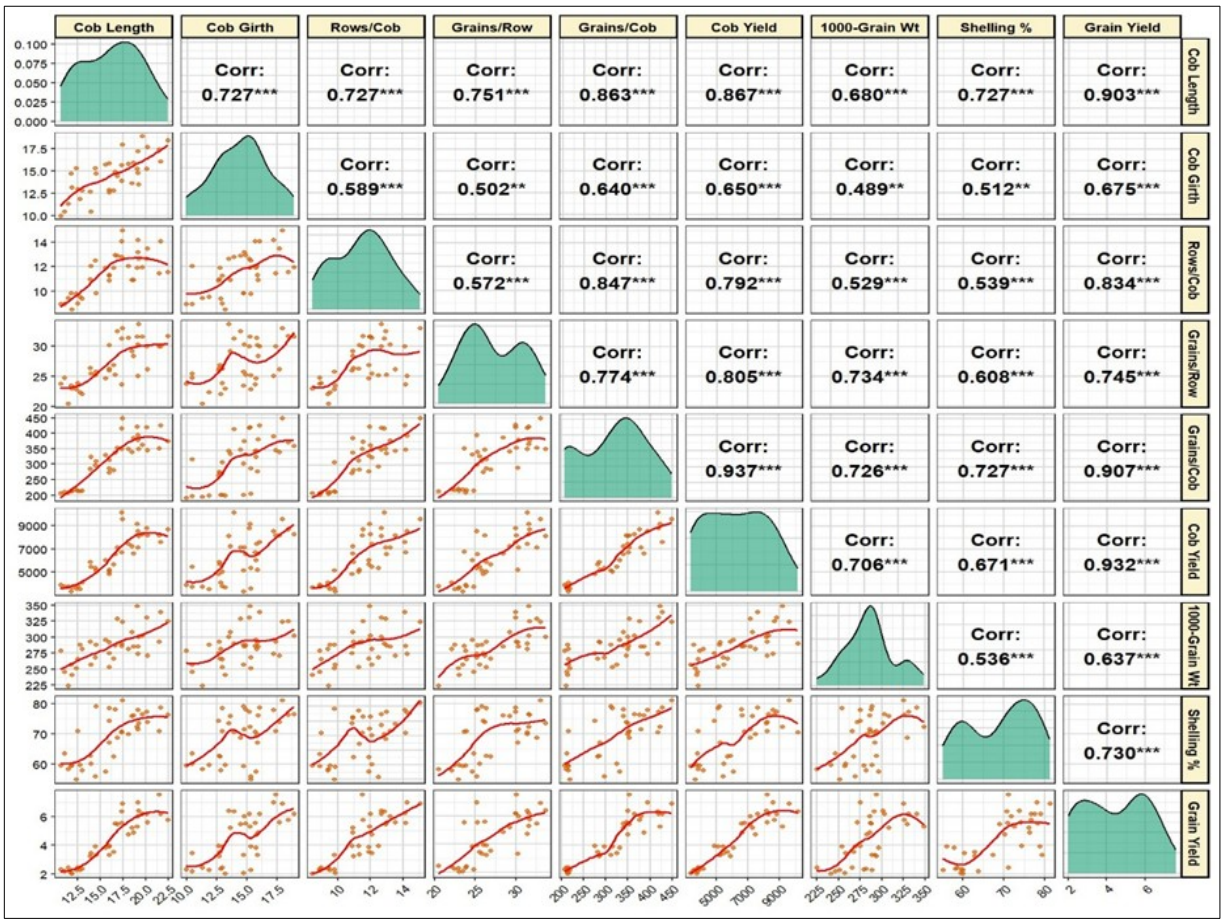



**Fig. 4.** Correlogram and scatterplot matrix illustrating Pearson's correlation among maize yield and attributing traits. This multi panel matrix shows the interrelationships among different yield attributes. The lower diagonal presents bivariate scatterplots with fitted trendlines, central diagonal displays density distributions for each individual trait and upper diagonal reports Pearson correlation coefficients with corresponding significance levels ($p < 0.05$, $^{**}p < 0.01$ and $^{***}p < 0.001$).

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However, supplementing this reduced dose with foliar nano-urea in $T_7$ (75 % RDN + nano-urea) reversed this physiological penalty. The conjoint $T_7$ treatment achieved structural cob dimensions and final grain yields statistically comparable to the $T_4$ standard. This indicates that high-efficiency stomatal uptake of nano-scale nitrogen effectively bypassed nutrient-loss mechanisms inherent to acidic soils, ensuring a continuous supply of nitrogen during the critical grain-setting phase (19). Furthermore, the potential of foliar nutrition was most evident in the fully optimised $T_8$ (100 % RDN + nano-urea) treatment. While the $T_4$ baseline provided an adequate vegetative framework, the addition of nano-urea in $T_8$ pushed the crop toward its maximum genetic potential. This treatment yielded the highest absolute values for grains per cob, significantly outperforming the absolute control. The stark contrast between the $T_3$ and the $T_8$ demonstrates that while soil N is essential for establishing early plant development, targeted foliar spray is vital for delaying canopy senescence, sustaining NAR and ultimately securing the survival of grain sites on the cob (20, 21).

## Yield

The comprehensive yield analysis clearly demonstrates the varying efficacy of nitrogen management strategies with final grain and biological yields significantly influenced by both the source and methods of nitrogen application (Fig. 5 and 6). The absolute control ($T_1$: N0 %) and foliar only ($T_5$ and $T_9$) consistently recorded the lowest metrics across all parameters thereby confirming that basal soil nitrogen is an irreplaceable prerequisite for initial vegetative establishment. Under fully supplied conditions, however, the synergistic effect of nano-urea foliar spray was evident. The $T_8$ (N100 % + nano-urea) treatment recorded the highest median grain yield and biological yield of the entire trial. Notably, when comparing full-dose conjoint applications, $T_8$ demonstrated profound superiority and consistency over $T_{12}$ (N100 % + 2 % prilled urea spray). While $T_{12}$ achieved high maximum yields, it exhibited substantial variability, as evidenced by exceptionally wide interquartile ranges in both stover and biological yield (Fig. 7). This erratic performance is often attributed to the limitations of conventional foliar urea, which can induce subtle leaf scorching or osmotic stress, thereby leading to inconsistent photosynthate assimilation. In contrast, the data distribution of $T_8$ suggests that nano-urea was assimilated highly efficiently through the stomata without phytotoxicity, ensuring reliable and maximum expression of the crop's genetic yield potential. Beyond absolute yield maximisation, the trial definitively demonstrates the compensatory potential of nano-urea. The standard practice ($T_4$: N100 %) established the baseline for acceptable commercial yield (6.24 t $ha^{-1}$). However, the $T_7$ (N75 % + nano-urea) treatment statistically at par (5.79 t $ha^{-1}$) and in median values slightly exceeded, the grain yield of the $T_4$ baseline. This finding confirms that a 25 % reduction in soil-applied urea a critical economic and environmental advantage in acidic soils prone to rapid leaching incurs no agronomic penalty when supplemented with foliar spray of nano-urea (22, 23). This result is also reported by recent studies in the acidic hill soils of Northeast India, where 25 % reduction of conventional urea was successfully replaced by nano-urea foliar application in fodder maize without significant loss in yield (24). The targeted delivery of nano-urea directly to the foliage during peak reproductive demand successfully and sustaining source capacity (leaves) to fully fill the expanded sink (cob) (21). Furthermore, harvest index (HI) data (Fig. 8) demonstrate that the increases in total biological yield observed in the optimised treatments were accompanied by proportional dry matter partitioning to the grain, avoiding excessive vegetative luxury consumption. Specifically, treatments $T_7$ and $T_8$ maintained high median harvest index (HI) values (approaching 0.38). From a physiological perspective, this indicates that foliar nano-urea application supported efficient source-sink dynamics during the reproductive phase. Rather than primarily stimulating vegetative biomass (stover), the sustained photosynthetic capacity supported by the previously observed improvements in leaf area duration likely ensured a continuous supply of post-anthesis photosynthates. This extended source activity facilitated the efficient translocation of assimilates from the vegetative tissues into the economic sink (developing grains), ensuring that enhanced growth kinetics effectively translated into improved final grain yield. The study shows that nano-urea can replace 25 % of conventional RDN without statistically reducing maize grain yield. Though, these results are based on a single season, a multi-year and multi-location trials are necessary to confirm the findings and ensure that nano-urea can be incorporated across different agro-ecological zones.

## Nitrogen use efficiency and economics

Nitrogen use efficiency (NUE) of maize was influenced by foliar urea and different basal nitrogen levels (Table 1). The highest agronomic efficiency (AE) of 30.69 kg grain $kg^{-1}$ of applied N was obtained in $T_7$ (75 % RDN + nano-urea) which was statistically similar to $T_8$ (100 % RDN + nano-urea) and $T_4$ (100 % RDN). The reduction in basal nitrogen to 50 % ($T_2$, $T_6$ and $T_{10}$) led to lower AE values. Apparent recovery efficiency (RE) had the highest value for $T_8$ (75.58 %), which was statistically similar to $T_7$ (72.13 %) and $T_4$ (65.62 %). The foliar nano-urea ($T_7$) was statistically superior to the 2 % prilled urea spray ($T_{11}$) in terms of both indices at 75 % basal N rate. The statistically at-par response of $T_7$ to $T_4$ indicates that the replacement of 25 % basal nitrogen with foliar nano-urea does not affect source-sink balance in reproductive growth stages (1). As a result, maize plants showed higher N recovery and N partitioning toward the grain development, which led to higher grain yield per unit of applied fertiliser (7, 23).

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**Table 1.** Nitrogen use efficiency and economics of maize as influenced by different nitrogen management

| Treatments | Agronomic efficiency (kg grain/kg N) | Apparent recovery efficiency (%) | Net returns (×1000 ₹/ha) | Benefit-cost (B : C) Ratio |
|---|---|---|---|---|
| $T_2$ ($N_{50}$ %) | 16.33$^{c}$ | 33.22$^{c}$ | 29.64$^{d}$ | 0.74$^{d}$ |
| $T_3$ ($N_{75}$ %) | 25.36$^{ab}$ | 58.02$^{b}$ | 61.05$^{c}$ | 1.50$^{c}$ |
| $T_4$ ($N_{100}$ %) | 26.09$^{a}$ | 65.62$^{ab}$ | 81.42$^{ab}$ | 1.98$^{ab}$ |
| $T_6$ ($N_{50}$ % + NUS) | 18.43$^{bc}$ | 41.39$^{c}$ | 31.27$^{d}$ | 0.75$^{d}$ |
| $T_7$ ($N_{75}$ % + NUS) | 30.69$^{a}$ | 72.13$^{ab}$ | 71.37$^{bc}$ | 1.69$^{bc}$ |
| $T_8$ ($N_{100}$ % + NUS) | 30.45$^{a}$ | 75.58$^{a}$ | 92.81$^{a}$ | 2.18$^{a}$ |
| $T_{10}$ ($N_{50}$ % + 2 % PUS) | 15.70$^{c}$ | 31.97$^{c}$ | 29.63$^{d}$ | 0.72$^{d}$ |
| $T_{11}$ ($N_{75}$ % + 2 % PUS) | 25.34$^{ab}$ | 59.38$^{b}$ | 63.05$^{c}$ | 1.52$^{c}$ |
| $T_{12}$ ($N_{100}$ % + 2 % PUS) | 25.20$^{ab}$ | 64.76$^{ab}$ | 80.84$^{ab}$ | 1.92$^{ab}$ |
| SEm (±) | 2.36 | 5.21 | 4.57 | 0.11 |
| CD ($p$ = 0.05) | 7.02 | 15.47 | 13.42 | 0.32 |

*NUS: nano-urea spray; PUS: prilled urea spray; SEm: standard error of the mean; CD: critical difference.

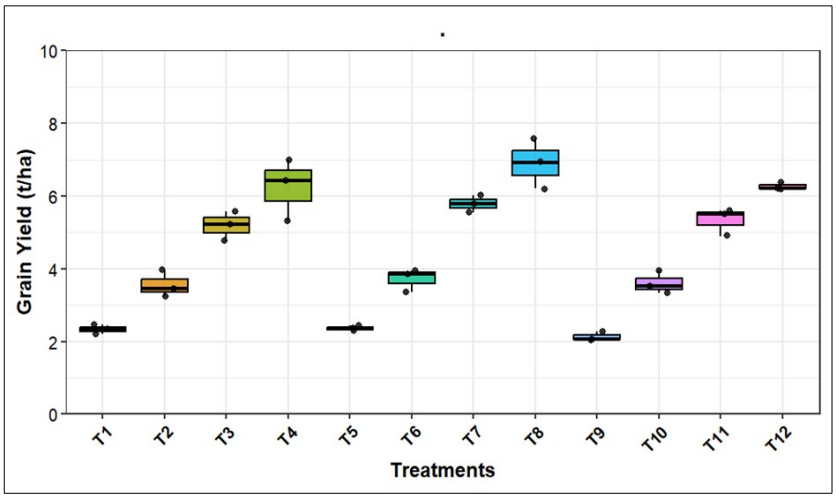



**Fig. 5.** Faceted box and whisker plots illustrating grain yield of maize under different nitrogen management.

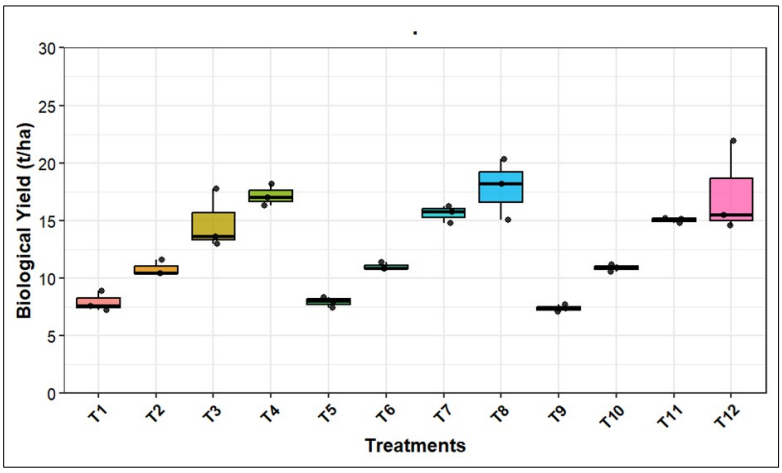



**Fig. 6.** Faceted box and whisker plots illustrating biological yield of maize under different nitrogen management.

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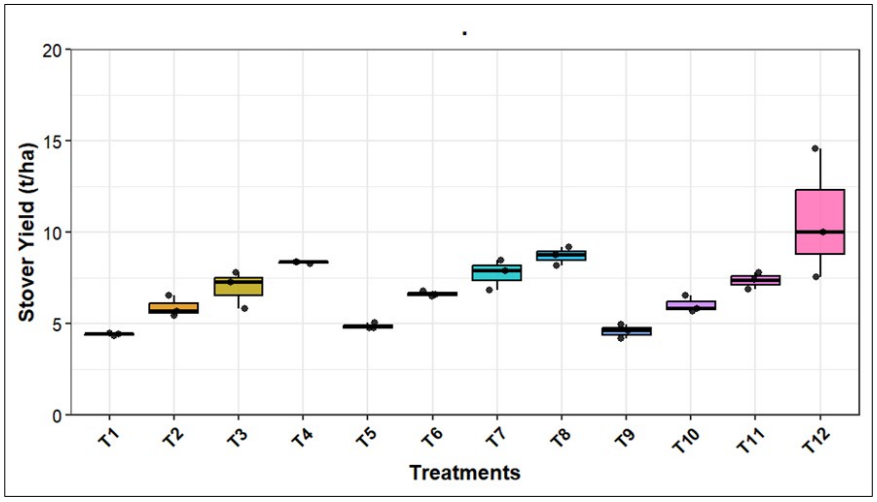



**Fig. 7.** Faceted box and whisker plots illustrating stover yield of maize under different nitrogen management.

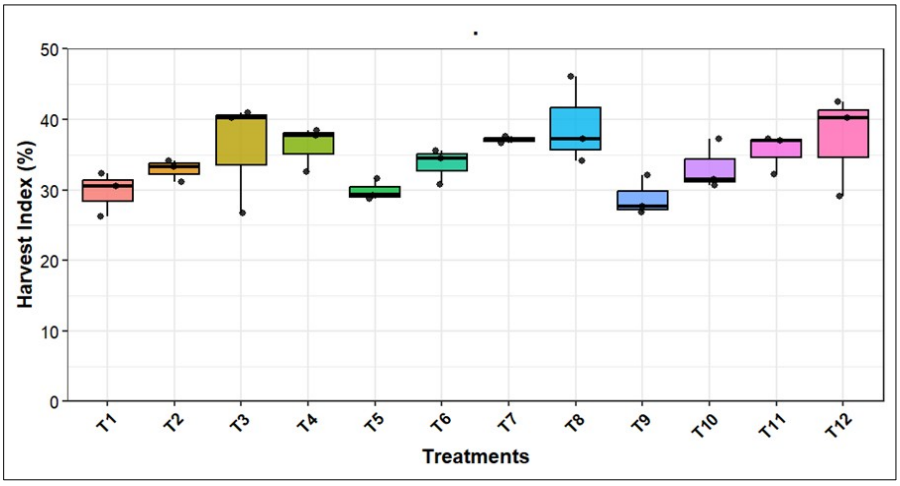



**Fig. 8.** Faceted box and whisker plots illustrating harvest index of maize under different nitrogen management. These faceted boxplots depict the median (bold central line), interquartile range (box) and overall statistical spread (whiskers) for biological yield, grain yield, stover yield and harvest index.

Such treatments also had an impact on economic viability. Treatment $T_8$ (100 % RDN + nano-urea) brought the highest net returns (92810 ₹/ha) and benefit-cost (B : C) ratio (2.18). This profitability is due to higher grain and stover production which compensate for the extra expense of this nano-urea formulation and application (18). The basal nitrogen was reduced to 75 %, as in $T_7$ (foliar nano-urea) which resulted in B:C ratio of 1.69 and net return of 71372 ₹/ha, which were statistically at par with basal application control ($T_4$; net return 81423 ₹/ha, B : C 1.98). This shows that there is an economic alternative to reduce N application in the soil by 25 %, which is provided by foliar nano-urea (23). This is cost effectiveness because of the higher nutrient recovery rate of nano-fertilisers (7, 20). On the other hand, only foliar application of nano-urea ($T_5$ and $T_9$) caused economic losses, highlighting that they may not replace basal N application in maize, but are rather used as supplements to it (1, 21).

## 4. Conclusion

The integration of foliar nano-urea spray into maize cultivation offers a viable pathway to overcome the low nitrogen use efficiency inherent to acidic soils. This study conclusively demonstrates that the conjoint application of conventional urea with foliar nano-urea spray not only maximises absolute crop productivity but also enables substantial reductions in conventional fertiliser usage. Physiological profiling and yield analyses confirm that supplementing a 75 % basal nitrogen dose with two foliar nano-urea sprays can mitigates the 25 % soil applied deficit. This strategy generated a physiological footprint and final grain yield statistically equivalent to the 100 % standard agronomic practice without incurring any yield penalty. This 25 % nitrogen substitution approach optimised nitrogen use efficiency (NUE). The agronomic efficiency (AE) and apparent recovery efficiency (RE) of the 75 % basal nitrogen plus nano-urea treatment remained statistically comparable to the fully fertilised control, while

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outperforming conventional 2 % prilled urea sprays. Furthermore, the findings show the superiority of nano-urea over conventional 2 % prilled urea sprays. Nano-urea treatments provided highly consistent, low-variance yield maximisation by ensuring rapid stomatal assimilation and avoiding the micro-osmotic stress and erratic performance associated with foliar spray of conventional urea. By effectively bypassing the leaching and various nutrient loss mechanisms of acidic soils, nano-urea sustained the leaf area duration (LAD) and optimised source-sink partitioning during peak reproductive demand. Economically, while the 100 % basal nitrogen dose supplemented with nano-urea generated the highest net returns, the 75 % basal nitrogen plus nano-urea treatment maintained a benefit-cost (B : C) ratio and net returns statistically at par with the 100 % standard practice. From a practical standpoint, adopting a 25 % nitrogen substitution strategy with nano-urea offers dual benefits, reducing the economic burden and environmental footprint of excessive soil nitrogen applications while sustaining farmer yields. As these results are from a one season experiment multiyear, multi-location trials (diverse agro-climatic zones and soil pH) are recommended. Such studies will be essential to validate the long-term soil nutrient mining, environmental dynamics, economic viability and systemic stability of nano-urea substitution in global maize production systems.

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## Authors' contributions

SR conducted the field trials, performed data curation, formal analysis and prepared the original draft of the manuscript. RKS, PKU, KS, SSR and PS[1] was responsible for conceptualisation, validation, provision of resources, supervision and manuscript review and editing. VT, PS[2] and KK contributed to visualisation, critical review and editing of the manuscript. SP and SK contributed to validation and final review and editing of the manuscript. All authors read and approved the final manuscript [PS[1] stands for Preeti Singh and PS[2] for Prakash Sonnad].

## Compliance with ethical standards

### Conflict of interest

Authors do not have any conflict of interests to declare.

### Ethical issues

None

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

During the preparation of this work, the authors used Google Gemini for grammatical corrections and language editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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