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# Efficacy of Nano Urea on Nitrogen Use Efficiency of Irrigated Maize under Temperate Ecology

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***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

A field experiment was conducted during the Kharif-2022 season at the Agronomy Research Field, FOA, SKUAST-Kashmir, to investigate the efficacy of nano-urea in improving nitrogen-use efficiency in irrigated maize. Ten treatments were evaluated viz., T1: Control, T2: Recommended dose of Nitrogen (RDN) as basal (prilled urea), T3: 75% RDN + 1 spray nano-urea at 2 ml $L^{-1}$ (60 DAS), T4: 75% RDN + 1 spray at 4 ml $L^{-1}$ (60 DAS), T5: 50% RDN + 2 sprays at 2 ml $L^{-1}$ (30 and 60 DAS), T6: 50% RDN + 2 sprays at 4 ml $L^{-1}$ (30 and 60 DAS), T7: 25% RDN + 2 sprays at 6 ml $L^{-1}$ (30 and 60 DAS), T8: 25% RDN + 2 sprays at 8 ml $L^{-1}$ (30 and 60 DAS), T9: 25% RDN + 1 spray at 6 ml $L^{-1}$ (60 DAS), T10: 25% RDN + 1 spray at 8 ml $L^{-1}$ (60 DAS). The experiment was carried out following a randomized complete block design with three replications. Results revealed that treatment T6 (50% RDN as basal + 2 sprays at 30 and 60 DAS at 4 ml $L^{-1}$ of nano-urea) exhibited superior performance compared to the recommended nitrogen dose (T2) and other treatments in enhancing nutri-ent-use efficiency. Notably, treatment T6 demonstrated the highest nitrogen uptake in grain (101.92 kg $ha^{-1}$) as well as stover (67.41 kg $ha^{-1}$), surpassing all other treatments. Additionally, agronomic efficiency was significantly higher in T8, while physiological efficiency peaked in T6. Yield attributes and overall yield showed consistent improvements in treatments receiving nano-urea. Furthermore, treatments utilizing nano-urea demonstrated higher net returns and benefit-cost ratios, with T6 particularly standing out. These findings underscore the potential of foliar application of nano-urea to halve the recommended dose of prilled urea, thereby enhancing nitrogen uptake, nutrient-use efficiency, yield, and economic returns, while promoting sustainability in agriculture.

*Keywords: Economics; nano-urea; maize; nitrogen-use efficiencies; yield; yield attributes.*

## 1. INTRODUCTION

One of the world’s leading crops that serve as both food and fodder is maize. Around 1147.7 million metric tons of maize are currently produced worldwide on 193.7 million ha [1]. The average productivity accounts to 5.75 t $ha^{-1}$. India is the 4th largest maize producer when it comes to total area and ranked 7th largest in context of production among maize-growing countries [2]. Though rice and wheat tops the list, maize records as the third-ranked cereals in India [3]. It is a versatile crop with broad adaptability. Its cultivation is possible in all seasons, making it a global crop. Nevertheless, being an exhaustible crop, it demands plenty of nutrients for its growth. An important nutrient for maximizing maize production is nitrogen. It is an essential component of DNA molecules, which are necessary for cell division and reproduction, and amino acids, the fundamental units of proteins [4]. Therefore, managing the nutrients to suit the crop’s demand is of utmost importance. However, applying an excessive amount of nitrogen fertilizer can pose a threat to the ecosystem, which may also result in nitrogen seepage into subterranean water reserves. Generally, prilled urea (Fig. 1) is prevalent as the primary source of nitrogen. In 2019-20, urea constituted 82 % of the total consumption of nitrogenous fertilizers in India, accounting to 33.6 million tons [1]. Rarely does maize recover more than 50% of the applied N [5]. When prilled urea is applied as basal dose, nitrogen suffers losses through a variety of mechanisms, including leaching, volatilization of ammonia, runoff, additional losses of N in gaseous forms as well as immobilization, ultimately causing environmental pollution. As a consequence, the intended sites in the plant system may not receive the applied fertilizer as effectively, causing hindrance in promoting optimum growth and productivity of maize. Considerable research has been carried out in this field but a practical solution to this problem is still lacking. A way out to this problem could be the application of innovative nanotechnological approaches [6,7]. Nanotechnology-driven products, such as nano-fertilizers, offer promising advantages including controlled nutrient release and enhanced accessibility to plants. Additionally, they contribute to soil mineral characterization, facilitate a deeper understanding of the soil rhizosphere, and im-prove nutrient ion transport within the soil-plant system [8]. Nano-urea, a nano-fertilizer containing 4% total nitrogen (w/v) evenly dispersed in water, is commonly applied through foliar spray onto crops [7]. Due to their diminutive size (20-50 nm), nanoparticles exhibit rapid penetration through stomata and leaf openings (Fig. 2) upon application, facilitating efficient absorption by plant cells [9].

Consequently, this study aims to enhance the efficiency of applied fertilizer through foliar application of nano-urea.

## 2. MATERIALS AND METHODS

### 2.1 Site Description

The field experiment was laid out at Agronomy Research Farm, Wadura, SKUAST-K, India in 2022 (kharif). At an altitude of 1590 m amsl, the site is positioned at 34°21'N latitude and 74°23'E longitude. An average yearly precipitation of 812 mm is received at the site, primarily occurring as snow and rain from December to April. The entirety of rainfall received during the experimentation period was 432.4 mm with a mean maximum temperature of 28.07℃ and minimum temperature of 15.31℃ (Fig. 3). For evaluating initial nutrients, collection of the soil samples was done from upper 20 cm of soil profile. Initial soil analysis indicated that the soil was neutral in pH (6.77) and medium in available NPK (Table 1).

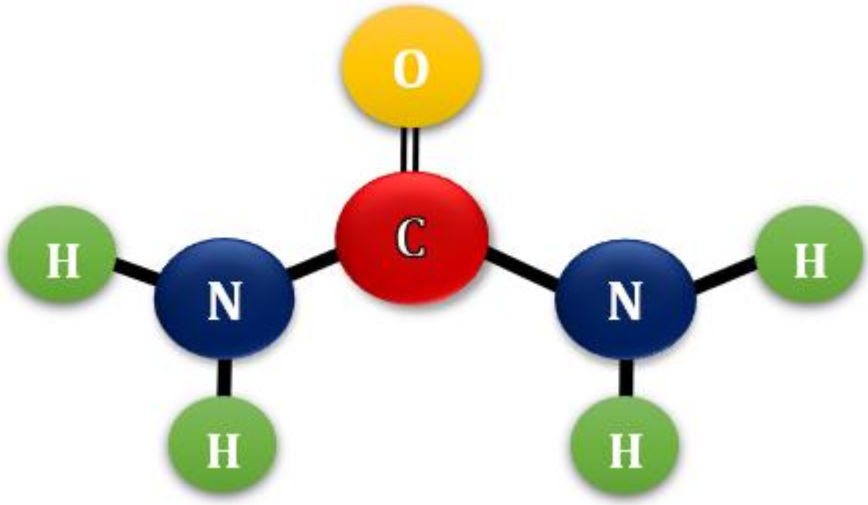


**Fig. 1. Structure of Urea**

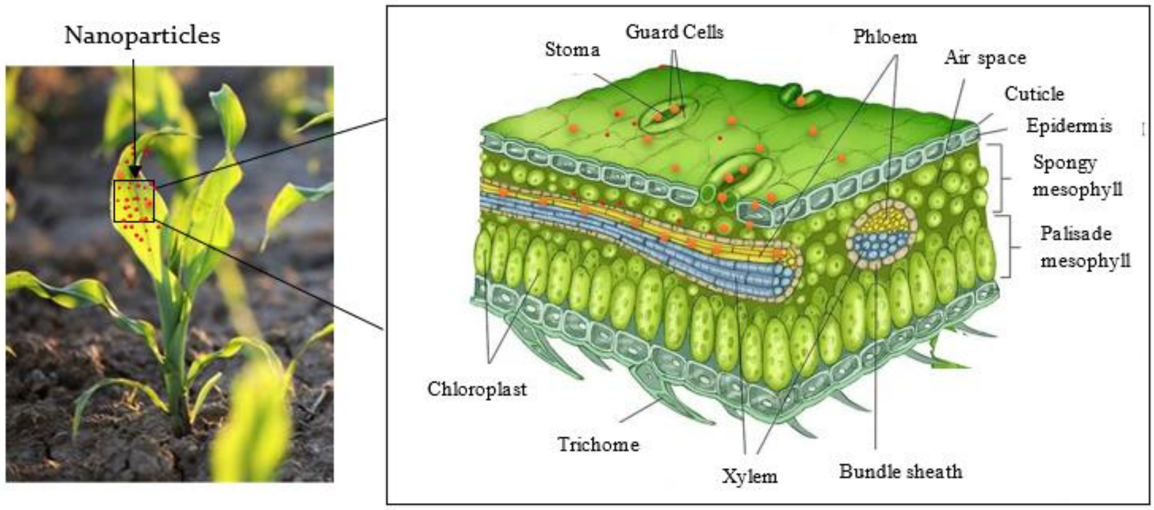


**Fig. 2. Schematic diagram of nanoparticle entry and transport in plant system.**

**Table 1. Initial Soil physico-chemical status of the site**

| Particulars | Value | Range | Method used |
|---|---|---|---|
| pH | 6.77 | Neutral | [10] |
| Electrical Conductivity (dSm-1) | 0.28 | Medium | [10] |
| Organic Carbon (%) | 0.71 | Medium | [11] |
| Available N (kg $ha^{-1}$) | 299.67 | Medium | [12] |
| Available P (kg $ha^{-1}$) | 17.20 | Medium | [13] |
| Available K (kg $ha^{-1}$) | 181.50 | Medium | [14] |

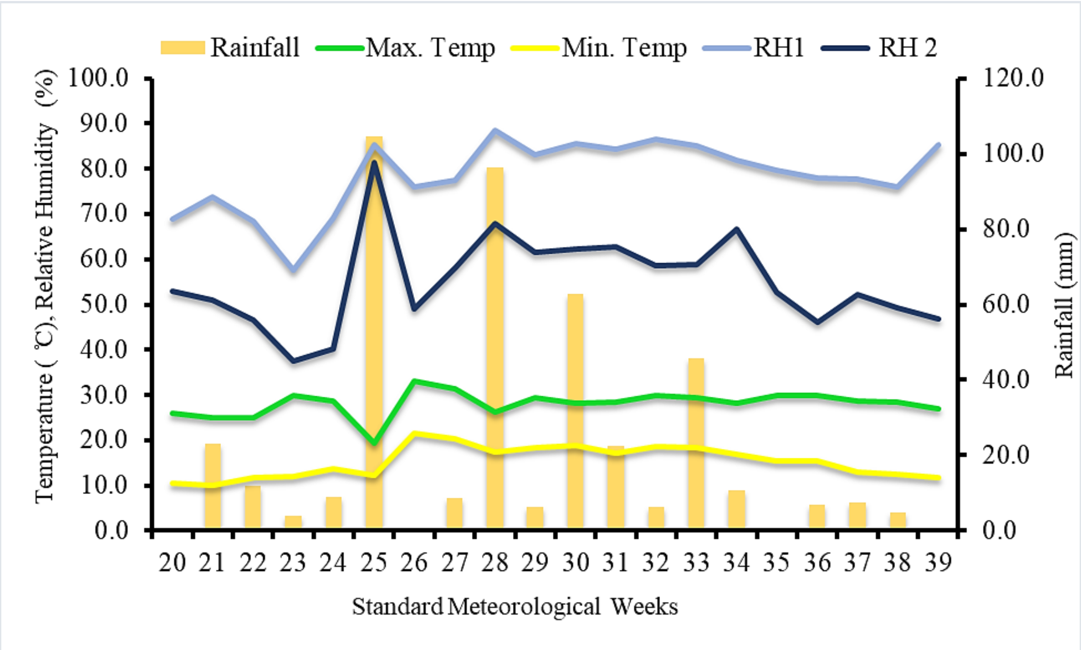


**Fig. 3. Weekly averaged meteorological data during crop growing season in *Kharif*-2022**

## 2.2 Experimental Details

The layout of the experiment followed a randomised complete block design with 10 treatments replicated thrice. Treatment details T1: Absolute Control, T2: 100% RDN (Recommended Dose of Nitrogen) through prilled urea at 150 kg $ha^{-1}$, T3: 75% RDN as basal dose + 1 spray nano-urea at 2 ml $L^{-1}$ at 60 DAS, T4: 75% RDN + 1 spray at 4 ml $L^{-1}$ at 60 DAS, T5: 50% RDN + 2 sprays at 2 ml L-1 at 30 and 60 DAS, T6: 50% RDN + 2 sprays at 4 ml L-1 at 30 and 60 DAS, T7: 25% RDN + 2 sprays at 6 ml $L^{-1}$ at 30 and 60 DAS, T8: 25% RDN + 2 sprays at 8 ml $L^{-1}$ at 30 and 60 DAS, T9: 25% RDN + 1 spray at 6 ml $L^{-1}$ at 60 DAS, T10: 25% RDN + 1 spray at 8 ml $L^{-1}$ at 60 DAS. Foliar applications were taken at 30 and 60 DAS (for 2 sprays) and at 60 DAS only (for 1 spray). The variety of maize used was Shalimar Maize Hybrid-5 (SMH-5) under irrigated condition. 100% $P_2O_5$ & $K_2O$ was common for all treatments except T1.

## 2.3 Crop Management Practices

Under optimum soil moisture condition, a fine tilth seed bed was established by conducting two ploughings with a tractor to attain the desired depth, followed by harrowing and planking. Plots were demarcated according to replications and treatments. A uniform dose of phosphorus and potassium at 75 and 40 kg $ha^{-1}$ $P_2O_5$ and $K_2O$ respectively (basal dose) was applied by broadcasting at the time of sowing to all plots. Nitrogen fertilizer, with different doses as per treatments was applied. The RDN (150 kg $ha^{-1}$) was applied as prilled urea at T2 (as per farmers' practice), where half dose (75 kg $ha^{-1}$) was applied at the time of sowing and remaining half in two splits at knee high (37.5 kg $ha^{-1}$) and tasseling stage (37.5 kg $ha^{-1}$). The basal dose in all the plots was applied through prilled urea whereas the remaining doses were applied either though prilled urea (top dressing) or through IFFCO nano-urea (foliar spray) as per treatments. Seeds were treated using Bavistin with Captan (1:1) at 2 g kg$^{-1}$ seed and sown at rate of 25 kg ha$^{-1}$ with a spacing of 75 x 20 cm. The crop was irrigated as needed, depending on the moisture levels in the soil. Special attention was given to ensure optimal soil moisture during the critical stages of crop growth viz., early knee high (21 DAS), tasseling (40 DAS) and grain filling (65 DAS) stage. Manual weeding was done 15-20 DAS. Post-emergence, Tembotrione (150 g a.i. ha$^{-1}$) was applied along with surfactant 30 DAS. To evaluate the yield, maize cob samples from the net plot area were manually harvested, and the grains were separated from cobs through hand shelling.

## 2.4 Observations Recorded

Plant height was measured every 30 days on five plants within the designated plot area that were se-lected randomly. Measurements were taken from ground surface level to the flag leaf tip and aver-aged, with results recorded in centimeters according to treatment. For dry matter sampling, three plants in quadrant of 1 x 1 m from sampling rows were cut from surface of ground at 30 days inter-val. Sun-drying of the samples were done for 4-6 days, thereafter, oven-dried for roughly 24 hours at 65 ± 5°C until constant weight (g) was reached. Yield attributes and total yield were determined by randomly selecting five plants from the designated plot area. The mean of number of cobs per plant was calculated after tagging and counting each cob. Additionally, the average length of tagged plant cobs was assessed by measuring from base to tip. Likewise, to establish the cob diameter, girth of the harvested cobs from tagged plants was calculated. Additionally, grain and straw yield was worked out in kg ha$^{-1}$ during crop harvest and later converted into q ha$^{-1}$. Following harvest in the field, the weight of each bundle from net plot was measured using an electronic balance and then approximated in q ha$^{-1}$. Harvested cobs from individual net plot were sun-dried after being separated from the stalk and husk. Eventually hand shelling is carried out to separate the grains. Drying of the grains was done till 15 % moisture content and grain yield was expressed in q ha$^{-1}$. By deducing the grain yield from the corresponding biological yield, the Stover yield was computed for every plot. In order to determine the harvest index, the grain yield was divided by total biological yield, which was then expressed in per-centage. Harvest index (%) was calculated by dividing economic yield with biological yield.

$$\text{Harvest index (HI)} = \frac{Grain\ yield}{Biological\ yield} \times 100$$

## 2.5 Plant Nutrient Analysis and Uptake

The nitrogen content of grain and stover was assessed by Kjeldahl digestion method wherein the grounded grain and stover samples were digested individually with concentrated sulphuric acid to determine its content. Further, the uptake of nutrient was calculated using the formula:

$$\text{Nutrient uptake} = \frac{Nutrient\ content(\%) \times weight\ of\ dry\ matter}{100}$$

## 2.6 Nutrient Use Efficiencies

The nutrient use efficiencies (Apparent nutrient recovery and physiological efficiency) were calculated by the following formulae:

$$\text{Agronomic efficiency (AES)} = \frac{(Grain\ yield\ in\ fertilized\ plot) - (Grain\ yield\ in\ control\ plot)}{Quantity\ of\ fertilizer\ applied\ in\ fertilized\ plot}$$

$$\text{Partial Factor Productivity (PfP)} = \frac{Grain\ yield\ in\ fertilized\ plot}{Quantity\ of\ fertilizer\ applied}$$

$$\text{Apparent nutrient recovery (AN)} = \frac{(Total\ uptake\ in\ fertilized\ plot) - (Total\ uptake\ in\ control\ plot)}{Quantity\ of\ fertilizer\ applied\ in\ fertilized\ plot}$$

$$\text{Physiological efficiency (PE)} = \frac{(Grain\ yield\ in\ fertilized\ plot) - (Grain\ yield\ in\ control\ plot)}{(Total\ uptake\ in\ fertilized\ plot) - (Total\ uptake\ in\ control\ plot)}$$

## 2.7 Statistical Analysis

To analyze the variance, ANOVA method for RCBD was used to examine the data on various parameters that were gathered during the experiment. The analysis was done using OPSTAT and R software. For comparing the treatment means and analysing it, least square difference method was used at a 5% level of significance. The nitrogen uptake was correlated with grain and stover yield respectively using R software.

# 3. RESULTS

## 3.1 Growth Parameters

The highest plant height of 32.57 cm and maximum dry matter accumulation of 34.37 q ha$^{-1}$ were observed in the treatment consisting of 75% RDN (basal dose) along with one spray at 60 DAS using nano-urea at a concentration of 4 ml L$^{-1}$ ($T_4$). Notably, this performance was statistically comparable to treatments $T_3$, $T_6$, $T_2$, and $T_5$, which included 75% RDN with one spray at 60 DAS using nano-urea at 2 ml L$^{-1}$, 50% RDN with two sprays at 30 and 60 DAS using 4 ml L$^{-1}$, RDN alone, and 50% RDN with two sprays at 30 and 60 DAS using nano-urea at 2 ml L$^{-1}$, respectively (Tables 2 and 3). At 60, 90 DAS and harvest, application of 50 % RDN + 2 sprays @ 4 ml L$^{-1}$ of nano-urea ($T_6$) recorded highest plant height and dry matter accumulation which was statistically at par with 50 % RDN + 2 sprays (30 & 60 DAS) at 2 ml L$^{-1}$ ($T_5$). The percent increase in plant height of treatment T6 with respect to RDN was found to be 5.25 % at 60 DAS, 8.93 % at 90 DAS and 6.04 % at harvest. Likewise, the dry matter accumulation of treatment $T_6$ increased 7.03 % at 60 DAS, 11.43 % at 90 DAS and 11.08 % at harvest with respect to RDN. The lowest plant height and dry matter accumulation was observed in absolute control (no nitrogen application) treatment ($T_1$).

**Table 2. Influence of different treatments of nano-urea on maize plant height**

| Treatments | Plant height (cm) | | | |
|---|---|---|---|---|
| | **30 DAS** | **60 DAS** | **90 DAS** | **Harvest** |
| $T_1$ : Absolute Control | 20.67 | 75.80 | 120.44 | 128.30 |
| $T_2$ : Recommended dose (RDN) | 31.43 | 109.07 | 177.20 | 189.57 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml L$^{-1}$ | 32.57 | 109.93 | 177.99 | 188.04 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml L$^{-1}$ | 32.22 | 110.13 | 181.70 | 190.73 |
| $T_5$ : 50 % RDN + 2 sprays at @ 2 ml L$^{-1}$ | 31.40 | 111.23 | 185.43 | 194.07 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml L$^{-1}$ | 31.67 | 116.77 | 193.03 | 201.02 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml L$^{-1}$ | 26.43 | 101.67 | 168.07 | 179.51 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml L$^{-1}$ | 26.13 | 102.23 | 168.96 | 179.64 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml L$^{-1}$ | 25.83 | 88.73 | 152.20 | 159.80 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml L$^{-1}$ | 26.00 | 88.90 | 152.84 | 160.27 |
| SEm ± | 0.79 | 2.06 | 2.85 | 2.77 |
| CD (p≤0.05) | 2.36 | 6.12 | 8.47 | 8.22 |

** Sem± is standard error of means; CD(p≤0.05) is critical difference.*

**Table 3. Effect of different treatments of nano-urea on dry matter accumulation**

| Treatments | Dry matter accumulation (q ha$^{-1}$) | | | |
|---|---|---|---|---|
| | **30 DAS** | **60 DAS** | **90 DAS** | **Harvest** |
| $T_1$ : Absolute Control | 17.18 | 35.83 | 93.54 | 97.13 |
| $T_2$ : Recommended dose (RDN) | 31.65 | 74.83 | 134.39 | 139.62 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml L$^{-1}$ | 34.33 | 72.74 | 136.61 | 143.88 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml L$^{-1}$ | 34.37 | 73.23 | 140.40 | 145.65 |
| $T_5$ : 50 % RDN + 2 sprays at 2 ml L$^{-1}$ | 31.50 | 76.52 | 143.70 | 150.08 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml L$^{-1}$ | 31.74 | 80.09 | 149.75 | 155.09 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml L$^{-1}$ | 25.85 | 66.13 | 129.71 | 134.02 |
| $T_8$ : 25 % RDN + 2 sprays at @ 8 ml L$^{-1}$ | 26.05 | 67.03 | 129.49 | 133.36 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml L$^{-1}$ | 25.75 | 54.10 | 115.95 | 119.97 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml L$^{-1}$ | 25.58 | 55.08 | 117.42 | 120.90 |
| SEm ± | 0.98 | 1.24 | 2.03 | 1.79 |
| CD (p≤0.05) | 2.91 | 3.69 | 6.02 | 5.31 |

**Table 4. Effect of different treatments of nano-urea on yield attributes of maize**

| Treatments | Yield attributes | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No. of cobs plant$^{-1}$ | No. of rows cob$^{-1}$ | No. of grains row$^{-1}$ | Seed index (g) | Cob length (cm) | | Cob diameter (cm) | |
| | | | | | With husk | Without husk | With husk | Without husk |
| $T_1$ : Absolute Control | 1.18 | 12.07 | 21.02 | 24.20 | 14.89 | 13.06 | 14.89 | 13.06 |
| $T_2$ : Recommended dose (RDN) | 1.24 | 13.62 | 28.87 | 24.23 | 16.23 | 14.60 | 16.23 | 14.60 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml $L^{-1}$ | 1.20 | 13.86 | 29.44 | 24.64 | 16.43 | 15.13 | 16.43 | 15.13 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml $L^{-1}$ | 1.23 | 14.08 | 29.59 | 24.63 | 16.87 | 15.37 | 16.87 | 15.37 |
| $T_5$ : 50 % RDN + 2 sprays at 2 ml $L^{-1}$ | 1.25 | 14.46 | 31.13 | 24.72 | 16.87 | 15.17 | 16.87 | 15.17 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml $L^{-1}$ | 1.25 | 14.46 | 32.67 | 24.74 | 17.00 | 15.20 | 17.00 | 15.20 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml $L^{-1}$ | 1.20 | 13.48 | 26.63 | 24.40 | 16.27 | 14.63 | 16.27 | 14.63 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml $L^{-1}$ | 1.21 | 13.50 | 27.13 | 24.67 | 16.30 | 14.67 | 16.30 | 14.67 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml $L^{-1}$ | 1.21 | 12.93 | 25.17 | 24.22 | 16.20 | 14.50 | 16.20 | 14.50 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml $L^{-1}$ | 1.22 | 12.97 | 25.33 | 24.37 | 16.20 | 14.60 | 16.20 | 14.60 |
| SEm ± | 0.24 | 0.32 | 0.51 | 0.15 | 0.45 | 0.49 | 0.45 | 0.49 |
| CD ($p \leq 0.05$) | NS | 0.95 | 1.52 | NS | 1.34 | 1.45 | 1.34 | 1.45 |

### 3.2 Yield Attributes

The average number of cobs per plant and seed index remained unaffected by the various treatments of nano-urea. However, treatments $T_6$ (50% RDN + 2 sprays at 4 ml $L^{-1}$) and $T_5$ (50% RDN + 2 sprays at 2 ml $L^{-1}$) exhibited higher numbers of cobs per plant and seed index compared to other treatments. Notably, treatment $T_6$ recorded a significantly greater number of rows per cob (14.46), statistically similar to $T_5$, $T_4$ (75% RDN + 1 spray at 4 ml $L^{-1}$), $T_3$ (75% RDN + 1 spray at 2 ml $L^{-1}$ of nano-urea), and $T_2$ (RDN). Similarly, the no. of grains per row was significantly affected by different nano-urea treatments, with $T_6$ recording the highest no. of grains per row (32.67). The percent increase in the number of grains per row in $T_6$ compared to the recommended nitrogen dose treatment ($T_2$) was 13.16%. Furthermore, the length of cobs (with and without husk) across all treatments, except the control ($T_1$), did not differ significantly from each other. Treatment $T_6$ (50% + 2 sprays at 30 and 60 DAS at 4 ml $L^{-1}$ of nano-urea) exhibited the highest length of cob (17.00 cm and 15.20 cm, respectively). However, cob diameter (with and without husk) was not significantly affected by the different treatments. Overall, the control treatment ($T_1$) demonstrated the smallest recorded values for all yield attributes.

### 3.3 Yield

The treatment $T_6$, involving 50% recommended dose of nitrogen (RDN) with two sprays at 4 ml $L^{-1}$ of nano-urea, exhibited significantly superior grain yield of 76.61 q $ha^{-1}$ compared to other treatments, including RDN alone ($T_2$). $T_6$ demonstrated an impressive 18.86% increase in grain yield relative to the recommended nitrogen dose ($T_2$). Similarly, the biological yield mirrored this trend, with $T_6$ achieving a higher value of 169.66 q $ha^{-1}$, representing an 11.81% increase compared to $T_2$. Moreover, $T_6$ also showed elevated stover yield at 97.05 q $ha^{-1}$, statistically comparable to treatments $T_5$, $T_4$, and $T_3$. The percentage increase in stover yield for $T_6$ over the recommended dose ($T_2$) was calculated to be 7.06%. Conversely, the lowest recorded value was obtained in the control treatment ($T_1$), which received no nitrogen application. Furthermore, the application of nano-urea positively influenced the harvest index, with $T_6$ displaying a higher index compared to other treatments, as depicted in Fig. 4.

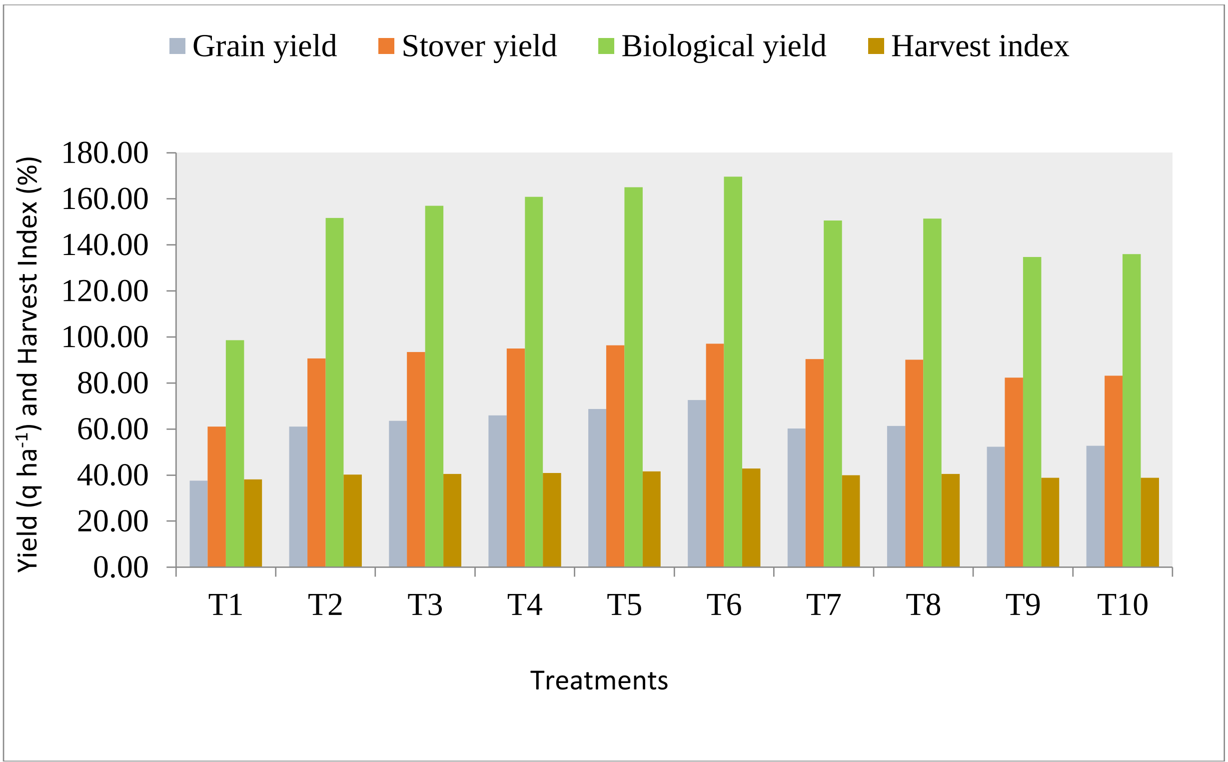


**Fig. 4. Yield (q $ha^{-1}$) and harvest index (%) of maize as influenced by different treatments**

### 3.4 Nutrient Studies

Various nano-urea treatments didn't have any significant effect on N content of grain and stover and also on protein content. However, data indicated that treatment with 50 % RDN + 2 sprays at 4 ml $L^{-1}$ applied at 30 and 60 DAS ($T_6$) recorded significantly higher N uptake in grain (101.92 kg $ha^{-1}$) and stover (67.41 kg $ha^{-1}$), which was statistically at par with 50 % RDN + 2 sprays at 2 ml $L^{-1}$ applied at 30 and 60 DAS ($T_5$) (Table 5). An increase of 22.00 % (in grain) and 12.73% (in stover) was observed in $T_6$ (highest N uptake) over the treatment with recommended dose of nitrogen ($T_2$) (Table 5).

### 3.5 Correlation Analysis

The analysis of data revealed that there is a significant association of yield with N content and uptake (Fig. 5). As revealed in Table 6, both grain and stover yield showed a positive correlation of 0.9 with N uptake.

**Table 5. Effect of nano-urea on N content and uptake in grain and stover and protein content**

| Treatments | N content (%) | | N uptake (kg $ha^{-1}$) | | Protein content (%) |
|---|---|---|---|---|---|
| | Grain | Stover | Grain | Stover | |
| $T_1$ : Absolute Control | 1.25 | 0.57 | 47.00 | 34.92 | 7.81 |
| $T_2$ : Recommended dose (RDN) | 1.37 | 0.67 | 83.54 | 59.80 | 8.55 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml $L^{-1}$ | 1.38 | 0.68 | 87.94 | 63.59 | 8.65 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml $L^{-1}$ | 1.39 | 0.69 | 91.81 | 65.43 | 8.70 |
| $T_5$ : 50 % RDN + 2 sprays at 2 ml $L^{-1}$ | 1.39 | 0.69 | 95.86 | 66.64 | 8.71 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml $L^{-1}$ | 1.40 | 0.69 | 101.92 | 67.41 | 8.77 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml $L^{-1}$ | 1.37 | 0.67 | 82.60 | 61.02 | 8.57 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml $L^{-1}$ | 1.38 | 0.68 | 84.67 | 61.20 | 8.63 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml $L^{-1}$ | 1.37 | 0.67 | 71.71 | 54.87 | 8.56 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml $L^{-1}$ | 1.37 | 0.67 | 72.19 | 55.38 | 8.56 |
| SEm ± | 0.02 | 0.02 | 2.05 | 0.82 | 0.16 |
| CD (p≤0.05) | NS | NS | 6.15 | 2.46 | NS |

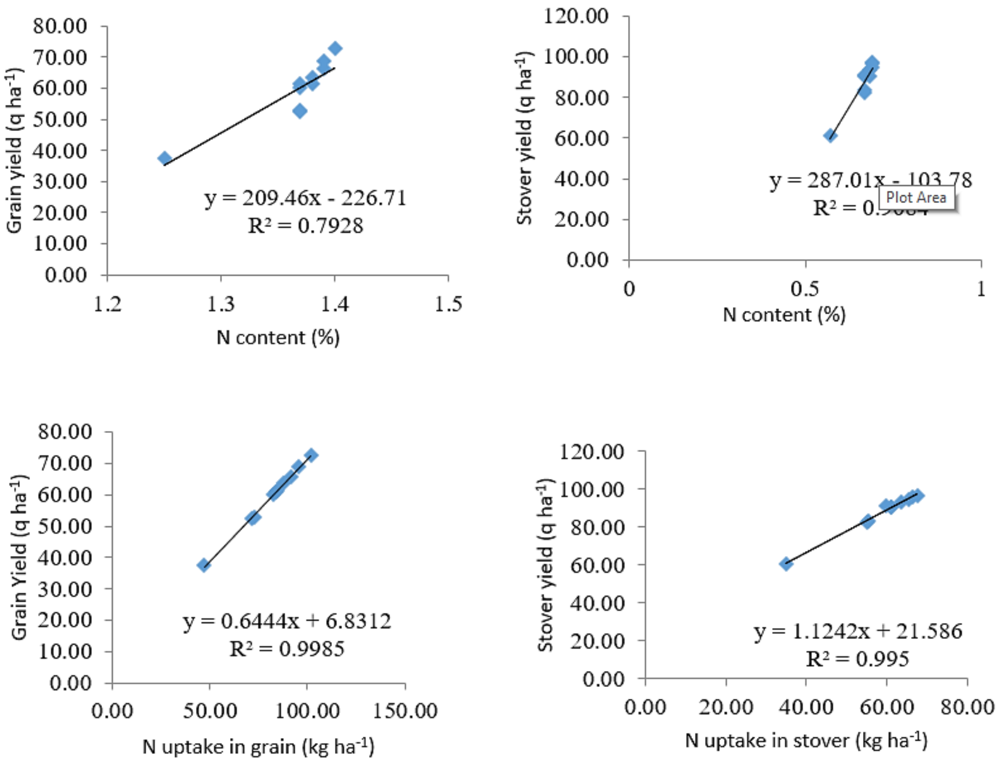


**Fig. 5. Response of grain and stover yield to N content and uptake**

**Table 6. Correlation coefficients of yield with nitrogen content and uptake**

| Yield | N content | N uptake |
|---|---|---|
| Grain Yield | 0.89 | 0.99 |
| Stover yield | 0.95 | 0.99 |

**Table 7. Effect of different treatments of nano-urea on nitrogen use efficiencies**

| Treatments | AE (kg grain $kg^{-1}$ N applied) | ANR (%) | PE (kg grain $kg^{-1}$ N uptake) | PFP (kg grain $kg^{-1}$ N applied) |
|---|---|---|---|---|
| $T_1$ : Absolute Control | - | - | - | - |
| $T_2$ : Recommended dose (RDN) | 16.14 | 40.95 | 38.22 | 42.69 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml $L^{-1}$ | 23.27 | 61.85 | 37.26 | 58.65 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml $L^{-1}$ | 25.80 | 66.90 | 37.60 | 61.17 |
| $T_5$ : 50 % RDN + 2 sprays at 2 ml $L^{-1}$ | 41.89 | 107.31 | 38.73 | 94.92 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml $L^{-1}$ | 45.62 | 116.24 | 40.04 | 98.57 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml $L^{-1}$ | 57.27 | 163.26 | 36.71 | 162.64 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml $L^{-1}$ | 61.90 | 168.80 | 37.09 | 167.01 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml $L^{-1}$ | 33.88 | 118.65 | 33.00 | 139.66 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml $L^{-1}$ | 35.14 | 121.11 | 33.12 | 140.79 |
| SEm ± | 2.66 | 3.06 | 0.81 | 2.30 |
| CD ($p \le 0.05$) | 8.04 | 9.11 | 2.42 | 6.95 |

**Table 8. Effect of different treatments of nano-urea on soil nutrient status**

| Treatments | N (kg $ha^{-1}$) | P (kg $ha^{-1}$) | K (kg $ha^{-1}$) | OC (%) | EC ($dSm^{-1}$) | pH |
|---|---|---|---|---|---|---|
| $T_1$ : Absolute Control | 207.19 | 15.78 | 173.37 | 0.68 | 0.27 | 6.74 |
| $T_2$ : Recommended dose (RDN) | 248.70 | 16.86 | 173.55 | 0.69 | 0.28 | 6.62 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml $L^{-1}$ | 235.68 | 16.77 | 174.71 | 0.69 | 0.28 | 6.65 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml $L^{-1}$ | 231.02 | 16.74 | 174.49 | 0.70 | 0.29 | 6.64 |
| $T_5$ : 50 % RDN + 2 sprays at 2 ml $L^{-1}$ | 200.68 | 16.96 | 176.90 | 0.70 | 0.28 | 6.67 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml $L^{-1}$ | 196.54 | 16.99 | 177.16 | 0.70 | 0.30 | 6.68 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml $L^{-1}$ | 191.84 | 16.90 | 175.87 | 0.68 | 0.29 | 6.69 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml $L^{-1}$ | 190.69 | 16.88 | 175.73 | 0.69 | 0.28 | 6.68 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml $L^{-1}$ | 209.73 | 16.92 | 176.35 | 0.68 | 0.27 | 6.73 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml $L^{-1}$ | 208.79 | 16.95 | 175.77 | 0.68 | 0.28 | 6.71 |
| SEm ± | 2.47 | 0.14 | 0.49 | 0.01 | 0.03 | 0.08 |
| CD ($p \le 0.05$) | 7.38 | 0.43 | 1.47 | NS | NS | NS |

**Table 9. Effect of different treatments of nano-urea on relative economics**

| Treatments | Cost of cultivation (₹) | Gross returns (₹) | Net returns (₹) | B:C ratio |
|---|---|---|---|---|
| $T_1$ : Absolute Control | 53,864.00 | 86,258.78 | 32,394.78 | 0.60 |
| $T_2$ : Recommended dose (RDN) | 56,939.09 | 1,38,667.67 | 81,728.58 | 1.44 |
| $T_3$ : 75 % RDN + 1 spray at 2 ml $L^{-1}$ | 56,968.45 | 1,44,296.00 | 87,327.55 | 1.53 |
| $T_4$ : 75 % RDN + 1 spray at 4 ml $L^{-1}$ | 57,568.45 | 1,49,422.50 | 91,854.05 | 1.60 |
| $T_5$ : 50 % RDN + 2 sprays at @ 2 ml $L^{-1}$ | 56,996.62 | 1,55,595.17 | 98,598.55 | 1.73 |
| $T_6$ : 50 % RDN + 2 sprays at 4 ml $L^{-1}$ | 58,196.62 | 1,63,401.17 | 1,05,204.55 | 1.81 |
| $T_7$ : 25 % RDN + 2 sprays at 6 ml $L^{-1}$ | 58,826.96 | 1,39,449.83 | 80,622.87 | 1.37 |
| $T_8$ : 25 % RDN + 2 sprays at 8 ml $L^{-1}$ | 60,026.96 | 1,37,089.50 | 77,062.54 | 1.28 |
| $T_9$ : 25 % RDN + 1 spray at 6 ml $L^{-1}$ | 57,026.96 | 1,19,667.00 | 62,640.04 | 1.10 |
| $T_{10}$ :25 % RDN + 1 spray at 8 ml $L^{-1}$ | 57,626.96 | 1,20,578.00 | 62,951.04 | 1.09 |

### 3.6 Nitrogen-use Efficiencies

The effects of different treatments of nano-urea on agronomic efficiency are summarized in Table 7. The highest agronomic efficiency (61.90 kg grain $kg^{-1}$ N applied) was observed in treatment $T_8$ (25 % RDN + 2 sprays (30 & 60 DAS) at 8 ml $L^{-1}$ nano-urea), which was statistically comparable to $T_7$ (25 % RDN + 2 sprays at 6 ml $L^{-1}$ nano-urea). Following closely were $T_6$ (50 % RDN as basal dose + 2 sprays at 4 ml $L^{-1}$ of nano-urea) and $T_5$ (50 % RDN as basal dose + 2 sprays at 2 ml $L^{-1}$ of nano-urea). Additionally, the highest apparent nutrient recovery of 168.80 % and partial factor productivity (167.01 kg grain $kg^{-1}$ N applied) were achieved when using 25 % RDN + 2 sprays (30 & 60 DAS) at 8 ml $L^{-1}$ of nano-urea ($T_8$), statistically comparable to $T_7$ (25 % RDN + 2 sprays at 6 ml $L^{-1}$). Moreover, the highest physiological efficiency of 40.04 kg grain $kg^{-1}$ N uptake was recorded in treatment $T_6$ (50 % RDN as basal dose + 2 sprays at 30 and 60 DAS at 4 ml $L^{-1}$ of nano-urea), which was statistically similar to $T_5$ (50 % RDN + 2 sprays at 2 ml $L^{-1}$) and $T_2$ (RDN). Conversely, treatment with the recommended dose of nitrogen ($T_2$) exhibited the lowest AE, ANR, and PFP.

### 3.7 Soil Characteristics

Table 8 outlines the characteristics of the soil under investigation. The data that was analyzed have indicated that different nano-urea treatments did not have a significant effect on soil pH, electrical conductivity, and organic carbon. However, treatment $T_2$ (RDN) exhibited the highest available nitrogen status in the soil at 248.70 kg $ha^{-1}$. Furthermore, it was observed that the treatment involving 50% of the recommended nitrogen dose applied as a basal dose, along with 4 ml $L^{-1}$ of nano-urea sprayed at 30 and 60 days after sowing (DAS), recorded the highest levels of soil available phosphorus and potassium compared to other treatments.

### 3.8 Relative Economics

The relative economic analysis involved calculating the production costs for each treatment, the associated marketable yield, and the standard prices per unit output. The economic analysis pertaining to economic analysis can be found in Table 9. From the table it is apparent that application of 50 % RDN + 2 sprays (30 & 60 DAS) @ 4 mL $L^{-1}$ ($T_6$) resulted in higher gross returns (₹ 1,63,401), net returns (₹ 1,05,205) and benefit cost ratio (1.81).

## 4. DISCUSSION

The T6 maize plants are subjected to better growth and yield due to the improved accessibility of the plants to nitrogen (N) that have been achieved through foliar spray of nano-urea. The unique properties of nano-particles include small size and large effective surface area let them penetrate easily into the plant leading to better uptake and absorption of nutrients [15]. Increased N availability performs a pivotal function in growth and development of plants by boosting auxin production, synthesizing carbohydrates, and promoting the production of organic compounds. These processes accelerate meristematic activity and shoot growth. Nitrogen also contributes to the structure of vital components such as cytochromes, chlorophyll, enzymes, purines, and pyrimidines. Consequently, enhanced photosynthetic activity, indicated by increased chlorophyll content, leads to larger plant heights and greater dry matter accumulation [16]. Additionally, nanoparticles have been shown to mobilize native nutrients, particularly phosphorus as per the studies done by researchers [17,18]. As phosphorus is crucial for root growth, it aids in the development of a robust root system, enhancing the absorption of other micronutrients from the soil. Additionally, nano-fertilizers facilitate the prolonged release of nutrients, thus ensuring a steady supply of nutrition to plants in T6, which positively impacts dry matter accumulation until harvest. This enhanced supply of nutrients was also discussed by several researchers [18].

The data analysis also revealed significant effects of all treatments on yield attributes. Notably, treatments receiving nitrogen through foliar application of nano-urea exhibited higher yield attributes compared to other treatments, including recommended dose of nitrogen (RDN). This enhanced nitrogen availability, as described above, likely encouraged greater assimilation of photosynthates towards grain production. The storage of foliar-applied nano-nutrients within plant cells allows for gradual release, thereby protecting against biotic and abiotic stresses leading to increased production of grain yield. Such findings were also stated by various scientists [19]. Furthermore, achieving higher yields necessitates an increase in total dry matter production per unit area. The total dry matter produced depends on the crop's photosynthetic effectiveness and the efficient functioning of vital plant activities [20]. Moreover, the partitioning of dry matter among various plant parts influences economic yield. Foliar application of nitrogen promotes more biomass, leading to a significant increment in stover yield. The higher grain and stover yield collectively contribute to higher biological yield, as experienced in the treatment T6 in the experimental field. The harvest index, denoting the translocation of photosynthates from source to sink, improved favorably through foliar application of nano-urea. Treatment T6 recorded the highest harvest index value among other treatments, consistent with findings of several researchers [21]. This is attributed to the storage and gradual release of surplus nutrient materials, reducing stress on plants and soils and resulting in higher biological and economic yields, thereby increasing the harvest index [22].

The data highlights the significant impact of various nano-urea treatments on N uptake in both grain and stover of maize crops. The observed increase in nutrient uptake can be attributed to higher nitrogen availability in the root zone, which enhances cellular metabolic activity. Additionally, foliar application of nano-urea reduces losses through denitrification and volatilization, leading to improved nutrient uptake and translocation within the plant. Similar observations have also been documented [22,23]. The increase in agronomic efficiency, as evidenced by the data, can be attributed to the smart delivery system of nanofertilizers, which enhance nutrient availability to the plant system, thereby increasing yield even with lesser amounts of applied nutrients [24]. Improved penetration and adsorption of nitrogen through foliar application are crucial for enhancing apparent nutrient recovery and mitigating losses due to leaching, volatilization, or denitrification. The effectiveness of nano-particles in increasing apparent nutrient recovery is influenced by factors such as size, reactivity, surface cover-age, and chemical composition [25]. Slowly released nano-fertilizers serve as an excellent substitute for conventional fertilizers by providing gradual nutrient release throughout the crop duration, thereby enhancing physio-logical efficiency and reducing nutrient losses [26-28].

Furthermore, the increase in soil availability of nutrients may result from reduced application of prilled urea, minimizing salt accumulation in the soil and reducing residual acidic effects, consequently enhancing nutrient availability to plants. Analysis of the data also reveals that the application of 50% of the recommended N dose along with two sprays of nano-urea (knee high and tasseling) at 4 ml $L^{-1}$ recorded the highest gross returns, net returns, and benefit-cost ratio. This can be attributed to the reduction in basal dose by 50%, which decreases fertilizer costs while maintaining or even increasing grain and stover yields, thereby enhancing profitability.

## 5. CONCLUSION

The findings of this study suggest that reducing the recommended dose of nitrogen by half and supplementing the remainder through foliar application of nano-urea can yield significant benefits in terms of minimizing fertilizer losses that resulted in noteworthy enhancements in growth parameters, and increased crop yield. Specifically, application of 50 % of the recommended dose of nitrogen as a basal dose, coupled with two sprays of nano-urea (at 30 and 60 days after sowing) at a concentration of 4 ml $L^{-1}$, emerged as the most efficient treatment compared to both 100% of the recommended nitrogen dose and other nano-urea treatments in terms of nutrient utilization, physiological efficiencies, and various yield attributes including grain yield, stover yield, biological yield, harvest index, as well as economic indicators such as net returns and benefit-cost ratio. Therefore, it can be concluded that the application of application of 50 % of the recommended dose of nitrogen as a basal dose, coupled with two sprays of nano-urea (at 30 and 60 days after sowing) at a concentration of 4 ml $L^{-1}$ has the potential to enhance nutrient-use efficiency and crop productivity, particularly in the temperate ecology of the Kashmir valley.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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