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IMPACT OF SCHEDULING PRILLED AND NANO-UREA ON GROWTH AND YIELD OF WHEAT (*Triticum aestivum* L.)

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ABSTRACT

A field experiment was conducted during *Rabi* 2024-25 at Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur to evaluate the effect of scheduling prilled urea and nano-urea on growth and productivity of wheat grown in a Vertisol. The experiment comprised nine treatments including control, varying levels of recommended nitrogen dose (RDN) and foliar application of nano-urea at different growth stages, laid out in a randomized block design with three replications. Results revealed that application of 100% recommended dose of fertilizer (RDF) produced significantly superior growth attributes and yield components compared with the control. The maximum grain yield (4.97 t ha^{-1}) and straw yield (7.06 t ha^{-1}) were recorded under 100% RDF, representing an increase of 49.7% and 30.3% respectively, over control. However, these yields were statistically comparable with treatments receiving 50% RDN supplemented with nano-urea foliar sprays, indicating the potential of nano-urea to partially substitute conventional nitrogen fertilizer without compromising productivity. Correlation analysis showed strong positive associations among growth and yield parameters, with grain yield exhibiting significant ($p \leq 0.01$) relationship with plant height, tiller number, chlorophyll index and grains per earhead. The findings suggest that nano-urea can partially substitute conventional nitrogen fertilizer without compromising wheat productivity under Vertisol conditions.

Keywords : Nano-urea, Nitrogen scheduling, Prilled urea, Sustainable nitrogen management, Vertisol.

Introduction

Wheat (*Triticum aestivum* L.) is most cultivated crop largely used for human and animal nutrition due to its excellent food value. It contains 12 % protein, 1.72 % fat, 69.60 % carbohydrate and 27.2 % minerals India is one of the major wheat producing countries, contributing 14% of the global production from an area of about 3.19 million ha with an average productivity of 3.56 tha^{-1} (FAOSTAT, 2024). It is estimated that wheat production should be increased by 60% to meet the demand of the growing global population by 2050 (Savadi *et al*., 2018).

Nitrogen (N) is a highly mobile and essential macronutrient required for the optimal growth and yield of crops. Wheat, being a nitrogen-demanding cereal, needs substantial amounts of this nutrient as it forms a key component of protoplasm, proteins, and chlorophyll. Conventionally, nitrogen is supplied mainly through urea, which enhances cell enlargement, plant height, and overall productivity (Havlin *et al*., 2014). However, in recent decades, the excessive use of prilled urea has led to a significant decline in nitrogen use efficiency (NUE), higher input costs, and environmental degradation due to nitrogen losses ranging from 40–70% through volatilization, leaching, and denitrification (Solanki *et al*., 2015). These issues are particularly evident in Vertisols, characterized by high clay content, high water-holding capacity but low permeability, often resulting in nutrient fixation and reduced nutrient availability (Staff, 2015). The widespread and often unregulated use of nitrogen fertilizers, especially urea in rice and wheat systems, has been further fueled by heavy government subsidies and the immediate visible effects on crop growth. Hence, there is a critical need to adopt innovative strategies that reduce prilled urea use, enhance NUE, and sustain soil health without compromising yields. Nanotechnology has recently offered such a pathway through the development of nano-fertilizers. Liquid nano-urea, in particular, has emerged as a novel nitrogen source that supplies nutrients precisely and efficiently through foliar applications (Kumar *et al*., 2021). Its nano-scale particle size, large surface area, and slow-release characteristics enhance nitrogen absorption and utilization by plants, potentially improving NUE by up to 45% (Rahale, 2010). Moreover, liquid nano-urea is lightweight and easy to transport, making it an economical alternative that reduces logistics and storage costs. However, research comparing its effectiveness with prilled urea under different application schedules in Vertisols is scarce. Considering the above factors, the present study was undertaken to assess how scheduled applications of prilled urea and nano-urea influence the growth and yield performance of wheat grown in a Vertisol.

Materials and Methods

The experimental site, climate and soil

The experiment was carried out during *Rabi* 2024-25 at the Research Field of BSP Soybean, JNKVV, Jabalpur, Madhya Pradesh. Jabalpur is located in the Kymore Plateau and Satpura Hills agro-climatic zone, has a subtropical climate with hot, dry summers and cool, dry winters. The Tropic of Cancer passes through Jabalpur, where average temperatures during November–December range from 6.4°C to 31.6°C, providing favourable conditions for winter crops. The physico-chemical properties of soil are presented (Table 1).

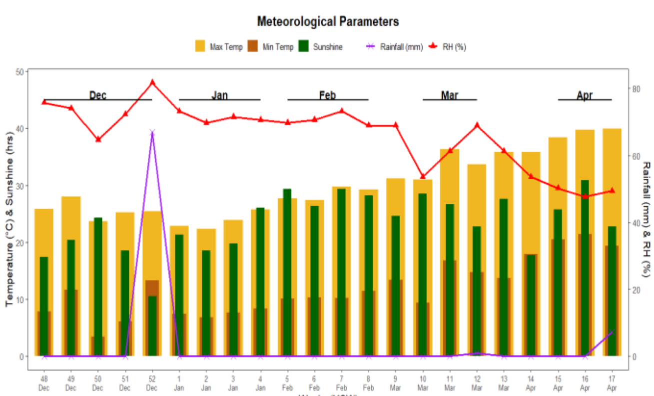

Fig. 1 : Maximum and minimum temperature (°C), sunshine (hours), rainfall (mm) and relative humidity (%) of the experimental site during winter season 2024-25

Table 1 : Soil properties of the experimental field at the beginning of the experiment

Soil property	Value
Soil depth	0-15
pH (1:2.5 soil: water) (Prasad *et al*. 2006)	7.35
Electrical conductivity (1: 2.5 soil-water extract at 25°C) (Piper 1966)	0.10 dS/m
Organic carbon (Walkley and Black 1934)	10.76 g/kg
Available nitrogen (Subbiah and Asija 1956)	203.70 kg/ha
Available phosphorus (Olsen *et al*., 1954)	16.6 kg/ha
Available potassium (Jackson, 1973)	202.3 kg/ha

Experimental design and treatment details

The experiment was conducted with 9 treatments and 3 replications in a randomized block design (RBD) on wheat variety GW 513. Treatments included various combinations of prilled urea (as recommended N) and nano-urea sprays at specified growth stages (25, 50, and 75 days after sowing), along with 100% PK application. The control (T_1) had no fertilizer input, while T_9 represented the full recommended dose of fertilizers (120:80:60 kg N:P_2O_5:K_2O ha^{-1}).

Table 2 : Treatment details

Treatment	Treatment Details
T_1	Control
T_2	0 N + 100% PK
T_3	Spray of nano-urea at 25, 50 and 75 DAS (0.25%)+ 100% PK
T_4	25% RDN as basal + spray of nano-urea at 25, 50 and 75 DAS (0.25%)+ 100% PK
T_5	50% RDN as basal + spray of nano-urea at 25, 50 and 75 DAS (0.25%)+ 100% PK
T_6	25% RDN as basal + 25% at CRI + spray of nano-urea at 50 DAS (0.25%) + 100% PK
T_7	25% RDN as basal + 25% at CRI + spray of nano-urea at 75 DAS (0.25%) + 100% PK
T_8	25% RDN as basal + 25% at CRI + spray of nano-urea at 50 and 75 DAS (0.25%) + 100% PK
T_9	100% RDF (N: P_2O_5: K_2O as 120:80:60 kg ha^{-1})

Growth parameters

Temporal (30, 60, 90 DAS and at harvest) changes in plant height, chlorophyll index and number of tillers m^{-2} were recorded in 5 randomly selected plants. The height was measured from the soil surface to the tip of tallest leaf before emergence of ear and up to tip of spike including awns after heading and expressed in cm, while chlorophyll index in leaves was determined using a handheld chlorophyll meter (Konica Minolta SPAD-502Plus). The numbers of tillers were counted from each sampling unit of one meter square and expressed as number of tillers meter^{-2}.

Yield attributes

Ear length of wheat was measured in cm using a ruler from base of the ear to its tip excluding awns and the same samples were used to record number of grains per ear. The 1000-grain weight was obtained using an analytical balance. Grain and straw yields were estimated from net plots and expressed in kg ha^{-1}. The harvest index was calculated as the ratio of economic yield to biological yield (Salisbury and Ross, 1986). It was calculated by using following formula:

$$Harvest\ Index\ (\%) = \frac{\text{Economic yield (kg ha)}^{-1}}{\text{Biological yield (kg ha)}^{-1}} \times 100$$

Statistical analysis and interpretation of data

The experimental data of each parameter thus obtained in the present investigation were tabulated and analyzed statistically by applying the standard technique the analysis of variance (ANOVA) for Randomized Block Design (RBD) was worked out and the significance of the treatment effect was tested with the help of 'F' (variance ratio) test to draw a valid conclusion as described by Gomez and Gomez (1984). The significance and non-significant effect of the different treatments was tested with the help of 'F' variance ratio test. Calculated 'F' value was compared with table value of 'F' at 5% levels of significance. Whenever the F-test indicated significant differences among treatments, the means were separated using Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. Standard error mean was computed and used to represent variability among replicates in graphical presentation. Pearson's correlation coefficients were computed and tested at 1% level of significance.

Results

The results obtained from the present investigation have been summarized under following heads:

Growth parameters

Nitrogen scheduling through prilled urea and nano-urea significantly influenced growth parameters of wheat at all developmental stages.

Plant height (cm)

Plant height increased progressively from 30 DAS to harvest across all treatments (Fig. 2), ranging from 22.9 to 31 cm at 30 DAS, 55.9 to 77.8 cm at 60 DAS, 82.7 to 103.3 at 90 DAS and 83.5 to 104.3 at harvest. Nitrogen application significantly influenced plant height at all stages, with the highest values consistently observed in plots receiving higher total nitrogen, split-dose applications and nano-urea sprays.

At 30 DAS, significantly higher plant height was recorded under 100% RDF (T_9) which was statistically at par with treatments combined of both basal and CRI-stage applications accompanied by nano-urea foliar sprays as well as those with basal nitrogen plus nano-urea sprays alone (T_4, T_5, T_6, T_7, T_8).

At 60 DAS, T_9 recorded significantly higher plant height (77.8 cm), showing an increase of 39.2% over control (T_1). Treatment T8 remained statistically at par with T_8, while control recorded the lowest (55.9 cm) value.

At 90 DAS and at harvest, treatment T_9 maintained superiority and remained statistically similar to T_8, whereas T_4, T_5, T_6 and T_7 formed intermediate groups.

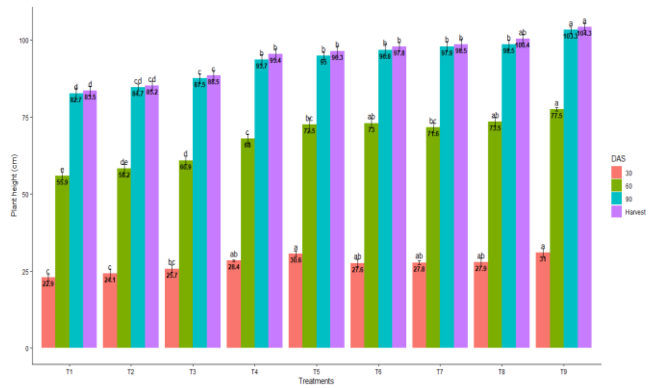

Fig. 2 : Effect of nitrogen application approaches on temporal changes in plant height of wheat

Tillers (m^{-2})

Number of tillers m^{-2} increased progressively from 30 DAS to 60 DAS and started decreasing slowly from 90 DAS in all the treatments (Fig. 3), ranging from 141 to 154 m^{-2} at 30 DAS, 224 to 239 m^{-2} at 60 DAS, 217 to 236 m^{-2} at 90 DAS and 212 to 233 m^{-2} at harvest.

At 30 DAS, 100% RDF (T_9) recorded the highest number of tillers (154 m^{-2}), representing an increase of 9.2% over control (T_1) and remained statistically at par with T_4, T_5, T_6, T_7, T_8, whereas T_1 recorded lowest number of tillers. Similar trends were observed at 60, 90 DAS and at harvest, T_9 recorded highest number of tillers (239, 236 and 233 m^{-2} respectively), representing an increase of 6.70%, 8.75% and 9.90% respectively over control T_9. These results suggest that higher nitrogen availability enhanced tiller production, particularly during the active vegetative phase, with split application of urea and foliar spray of nano-urea performing similarly to the full recommended dose.

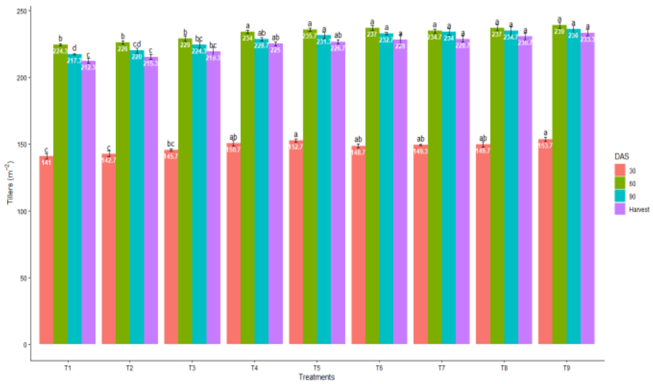

Fig. 3 : Effect of nitrogen application approaches on temporal changes in number of tillers in wheat

Chlorophyll index

Chlorophyll index varied significantly across treatments at all growth stages (Fig. 4). At 30 DAS, values ranged from 30.89 to 40.43. T_9 recorded the highest (40.43) chlorophyll index, showing an increase of 30.9% over control, while remaining statistically at par with T_4, T_5, T_6, T_7, T_8.

At 60 DAS, chlorophyll index increased further, ranging from 31.57 to 42.04. 100% RDF (T_9) recorded highest value (42.04), representing an increase of 33.2% over control and remained statistically comparable with T_4, T_5, T_6, T_7, T_8. The overlapping error bars among treatments indicate similar chlorophyll index status under adequate nitrogen supply.

At 90 DAS, chlorophyll index declined slightly, ranging from 21.73 to 32.23. T_9 again recorded the highest value (32.23), showing an increase of 48.3% over control, remaining at par with T_4, T_5, T_6, T_7, T_8. The lowest values were consistently observed under control.

Overall, higher chlorophyll index under the treatments receiving split-dose application of prilled urea along with nano-urea sprays indicates improved photosynthetic capacity.

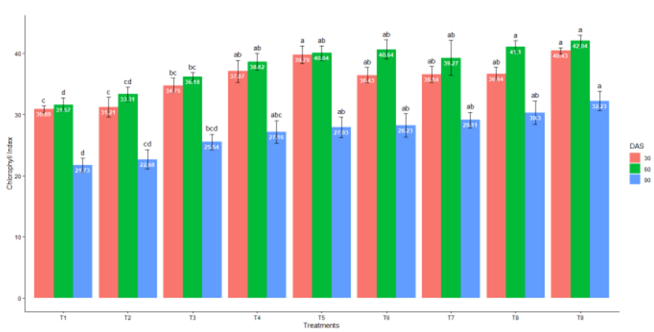

Fig. 4 : Effect of nitrogen application approaches on temporal changes in chlorophyll index in wheat

Yield attributes and yield

Yield attributes and yield varied significantly among treatments (Table 3).

Ear length (cm)

Ear length ranged from 10.9 to 13.4 cm and was significantly influenced among the different levels of nitrogen and nano-urea spray (Table 3). T_9 recorded maximum (13.4 cm) ear length, showing an increase of 22.9% over control and remained statistically at par with treatments T_4, T_5, T_6, T_7, T_8. However, minimum ear length (10.9 cm) was observed under control.

Grains per earhead

Number of grains per earhead ranged from 28.6 to 38.3 and was significantly improved by N supplementation. Highest (38.3) grains per earhead recorded at harvest with application of 100% RDF (T_9), showing an increase of 33.9% over control, which was at par with T_4, T_5, T_6, T_7, T_8 and lowest (28.6) grains per earhead under control treatment (T_1) (Table 3).

Test weight

A critical perusal of the data reveals the non-significant effect of different doses of urea and nano-urea sprays among the treatments on the test weight of wheat (Table 3). However, numerically higher (47.70) test weight was recorded under treatment T_9 (100% RDF), indicating an increase of 7.6% over control.

Grain yield and straw yield of wheat

Data pertaining to the grain yield in table 3 revealed that grain yield of wheat ranged from 3.29 t ha^{-1} to 4.97 t ha^{-1}. Application of 100% RDF (T_9) produced maximum (4.97 t ha^{-1}) grain yield which was statistically at par with treatments T_4, T_5, T_6, T_7, T_8, further minimum (3.32 t ha^{-1}) grain yield was recorded under control (T_1). Among the treatments, T_9 and T_8 recorded 49.7% and 44.9% increase respectively over T1. The overlapping error bars between T_9 and T_8 indicate similarity in performance.

Straw yield of wheat ranged from 5.42 t ha^{-1} to 7.06 t ha^{-1}. Treatment T_9 recorded maximum (7.06 t ha^{-1}) straw yield exhibiting a significant increase of 30.3% over control. Among the treatments accompanied of urea application and foliar sprays of nano-urea, T_4, T_5, T_6, T_7, T_8 were found significantly higher by 22.1%, 22.32%, 24.4%, 24.5% and 27.49% respectively over control.

Harvest index

Harvest index ranged from 37.99 to 41.30. Among the different levels of N and nano-urea spray, treatment with 100% RDF (T_9) recorded significantly maximum (41.30) harvest index, representing an increase of 8.7% over control and remained statistically on par with the treatments T_4, T_5, T_6, T_7, T_8 and minimum under control (T_1) (Table 3).

Table 3 : Effect of nitrogen application approaches on yield attributes of wheat.

Treatments	Yield attributes					
	Ear length (cm)	Grains per earhead	Test weight (g)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index
T_1	10.9	28.6	44.32	3.29	5.42	37.99
T_2	11.4	29.2	44.62	3.57	5.72	38.69
T_3	12.0	32.1	45.51	3.85	6.00	39.07
T_4	12.6	34.7	45.89	4.45	6.62	40.22
T_5	12.8	35.3	46.10	4.47	6.63	40.25
T_6	13.0	36.5	46.55	4.60	6.74	40.58
T_7	13.1	37.1	46.72	4.62	6.75	40.62
T_8	13.1	37.6	47.29	4.81	6.91	41.04
T_9	13.4	38.3	47.70	4.97	7.06	41.30
SEm±	**0.31**	**1.21**	**0.71**	**0.20**	**0.20**	**0.52**
CD (*p=0.05*)	**0.93**	**3.63**	**NS**	**0.60**	**0.60**	**1.57**

Correlation among growth and yield attributes

The correlation analysis (Fig. 5) revealed strong and positive associations among growth and yield attributes of wheat under scheduled application of prilled and nano-urea at $p \leq 0.01$ (Fig. 4), indicating a high degree of reliability in the observed relationships. Grain yield exhibited strong positive correlations with plant height, tillers m^{-2}, chlorophyll index and grains per earhead. Straw yield also exhibited a strong positive correlation with grain yield. Test weight showed a moderate positive association, while harvest index was positively correlated with most traits. Colour intensity represents the magnitude of the values, where lighter shades indicate lower values and darker red shades indicate higher values.

	GY	PH	T	CI	GPE	TW	SY	HI
GY	**1**							
PH	**0.85**	**1**						
T	**0.77**	**0.85**	**1**					
CI	**0.79**	**0.85**	**0.82**	**1**				
GPE	**0.76**	**0.89**	**0.74**	**0.73**	**1**			
TW	**0.64**	**0.73**	**0.56**	**0.59**	**0.66**	**1**		
SY	**0.79**	**0.86**	**0.71**	**0.69**	**0.80**	**0.75**	**1**	
HI	**0.67**	**0.78**	**0.62**	**0.52**	**0.78**	**0.70**	**0.84**	**1**

[GY- Grain yield, PH- plant height at harvest, T- tillers (m^{-2}) at 60 DAS, CI- chlorophyll index at 60 DAS, GPE- number of grains per earhead, TW- test weight, SY- straw yield, HI-harvest index].

Fig. 5 : Pearson rank correlation matrix depicting relationship among growth parameters and yield attributes of wheat under scheduled application of prilled and nano-urea ($p \leq 0.01$)

Regression analysis

Relationship between grain yield and straw yield

A strong positive linear relationship was observed between grain yield and straw yield (Fig. 6). The regression analysis produced equation y = -2.25 + 1.02x, with a coefficient of determination ($R^2 = 0.998$), indicating that straw yield explains nearly all the variability in grain yield. Grain yield increased consistently with increasing straw yield across the observed range 5.42 to 7.06 t ha^{-1}. The slope value close to unity suggests a nearly proportional increase between the two variables.

Relationship between grain yield and test weight

Grain yield increased linearly with test weight across the observed range 44.32 to 7.70 g. (Fig. 7) The regression analysis showed a strong positive relationship ($R^2 = 0.94$), indicating that 94% of the variation in grain yield is explained by test weight. The slope 0.5 suggests that for every 1 g increase in test weight, grain yield increased by approximately 0.5 t ha^{-1}. The data points closely followed the regression line, reflecting low variability and a consistent trend.

Relationship between grain yield and grains per earhead

Grain yield increased linearly with number of grains per earhead across the observed range 28.6 to 38.3. The regression analysis showed a very strong positive relationship ($R^2 = 0.981$), indicating that 98.1% of the variation in grain yield was explained by grains per earhead. The slope 0.16 suggests that each additional grain per earhead contributed approximately 0.16 t ha^{-1} increase in grain yield. That data points were closely aligned with the regression line indicating minimal variability and a highly consistent trend (Fig. 8).

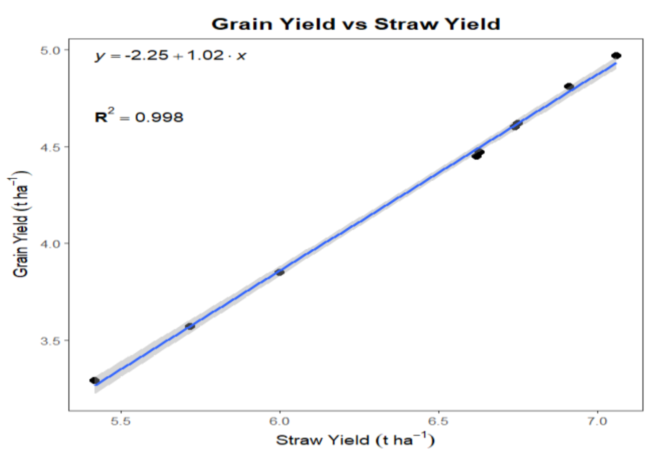

Fig. 6 : Relationship between grain yield and straw yield (t ha^{-1})

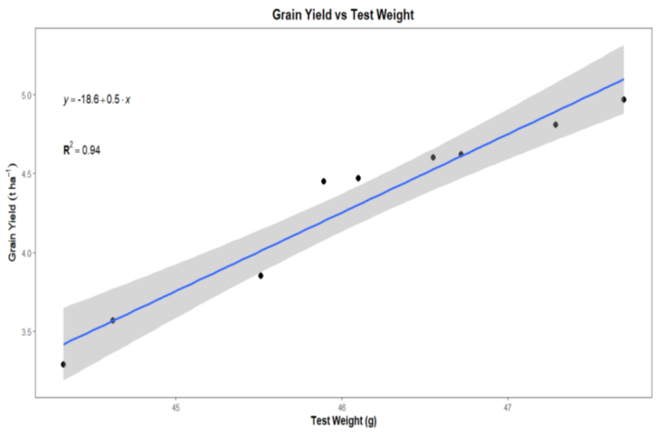

Fig. 7 : Relationship between grain yield and test weight showing a strong positive linear trend

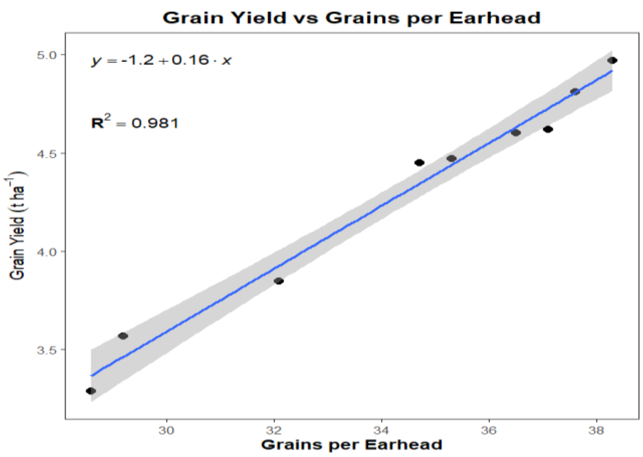

Fig. 8 : Relationship between grain yield and grains per earhead showing a strong positive linear association

Principal component analysis (PCA) of yield and yield attributes

PCA revealed that the first principal component (PC1) accounted for 98.7% of the total variation, while PC2 contributed only a negligible proportion of the variability (Fig. 9). All yield attributes, including grain yield, straw yield, grains per earhead, ear length and harvest index were positively loaded on PC1, indicating a strong positive association among these traits. The variable correlation plot further demonstrated that all traits were closely aligned and positioned near the circumference of the correlation circle, suggesting a high degree of representation and reliability of the variables in explaining the total variation. Test weight showed a slight deviation towards PC2, indicating that it contributed to a minor and independent component of variation. Overall, the PCA results indicated that grain yield was strongly influenced by associated yield attributes, which varied in a coordinated manner.

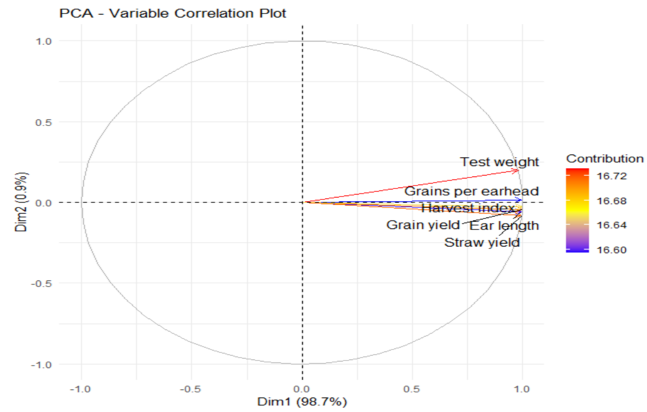

Fig. 9 : PCA variable coreelation plot depicting association among yield and yield attributing traits in wheat

Discussion

Nitrogen management significantly influenced growth and yield of wheat, clearly demonstrating the importance of synchronized nutrient supply. The superior performance of 100% RDF (T_9) along with its statistical parity with integrated nano-urea treatments (T_4-T_8) indicates that partial substitution of conventional urea with nano-urea can sustain crop performance without compromising yield. This reflects improved nitrogen use efficiency, which is a major concern in cereal based system.

Growth parameters

Plant height (cm)

The increase in plant height under higher nitrogen availability may be attributed to enhanced cell division, elongation, protein synthesis, as nitrogen is a key constituent of amino acids and structural compounds (Havlin *et al.*, 2014). However the comparable performance of treatments receiving reduced basal nitrogen along with nano-urea sprays suggests that foliar nano-urea effectively supplements crop nitrogen demand during later growth stages. This supports the hypothesis that nano fertilizers improve nutrients delivery efficiency due to their higher surface area and controlled release behaviour (Kumar *et al.*, 2021). Similar improvements in plant height under strategic nitrogen management have been reported by Singh *et al.* (2023) and Bala *et al.* (2024).

Tillers (m^{-2})

Tillering response further confirms the role of nitrogen in promoting vegetative growth. Increased tiller density under higher nitrogen treatments may be associated with enhanced cytokinin activity and carbohydrate availability, which stimulate axillary bud development (Chaturvedi, 2006). However, it is important to note that excessive nitrogen can sometimes lead to unproductive tiller; the absence of such effects in the present study suggests efficient nitrogen partitioning under both RDF and nano-urea treatments. Comparable findings were reported by Sarkar *et al.* (2023) and Dadmal *et al.* (2025), who observed that nano-urea supplementation maintained optimal tiller production even under reduced nitrogen input.

Chlorophyll index

Chlorophyll index, a representative for leaf nitrogen status and photosynthetic efficiency was significantly higher under RDF and integrated treatments. This indicates improved nitrogen assimilation and retention in leaf tissues. The strong association between nitrogen supply and chlorophyll content has been well documented (Bojovic and Markovic 2009). Notably, treatments receiving nano-urea sprays maintained chlorophyll levels comparable to RDF, suggesting that foliar application can effectively compensate for reduced soil applied nitrogen. This aligns with findings of Sikka *et al.* (2024). Bala *et al.* (2024) reported that split application of foliar nano-urea across different growth stages synchronized better with nitrogen demand, leading to increased chlorophyll index.

Yield attributes and yield

Ear length (cm) and Grains per earhead

Yield attributes such as ear length and grains per earhead showed significant improvement under optimized nitrogen management. This can be attributed to better assimilate partitioning during reproductive stages, supported by continuous nitrogen availability. Nitrogen plays a crucial role in spike development and grain setting by influencing enzyme activity and hormonal balance (Havlin *et al*., 2014). The statistical similarity between RDF and nano-urea based treatments highlights the efficiency of foliar nitrogen in supporting reproductive development, as also observed by Rawate *et al.* (2022) and Pal *et al.* (2023).

Test weight

Interestingly, test weight was not significantly affected by nitrogen treatments, suggesting that grain filling is more genetically regulated and less responsive to nitrogen supply beyond a threshold level. Similar non-significant responses have been reported by Biswas *et al.* (2024) and Kumar *et al*. (2023), indicating that nitrogen primarily influences sink size rather that individual grain weight.

Grain yield and straw yield of wheat

Grain and straw yield responses clearly demonstrate the advantage of to split application of urea as well as crop demand based foliar spray of nano-urea. The highest yield under RDF is expected due to maximum nutrient availability. However, the comparable performance of treatments with reduced nitrogen and nano-urea sprays is particularly important from a sustainable perspective. This indicates that nano-urea can partially replace conventional urea without yield penalty, thereby reducing nitrogen losses and input costs. Given that conventional nitrogen fertilizers suffer from 40-70% losses through volatilization, leaching and denitrification (Solanki *et al*., 2015), such strategies are highly relevant for improving nitrogen use efficiency. Similar conclusions have been drawn by Singh *et al.* (2023), Bala *et al.* (2024) and Sarkar *et al.* (2023), who reported that nano-urea based scheduling can maintain yield while reducing chemical nitrogen input.

Harvest index

The improvement in harvest index under optimized nitrogen treatments indicates translocation of assimilates towards economic yield. This suggests that balanced nitrogen supply not only enhances biomass production but also improves its portioning efficiency. Similar improvements in harvest index have been reported by Goud *et al.* (2022) and Bala *et al.* (2024).

Correlation among growth and yield attributes

Correlation analysis provided further insights into the interrelationships among traits. The strong positive correlation of grain yield with plant height, tillers, chlorophyll index and grains per earhead confirms that both structural growth and physiological efficiency contribute to yield formation. The positive association between chlorophyll index and grain yield highlights the importance of nitrogen mediated photosynthesis in biomass accumulation. These findings are consistent with earlier reports maximum (Ali, 2020 and Kaur, 2018). Moreover, the strong relationship between straw and grain yield indicates that total biomass production is a key determinant of economic yield, as reported by (Barraclough *et al*., 2010). The moderate association of test weight suggests its supportive but less dominant role in yield formation. Harvest index showed positive correlations with most of the traits, particularly with grain yield, suggesting efficient partitioning of assimilates towards grain under improved nitrogen management practices. Similar improvements in harvest index and yield under optimized nitrogen management have been reported in wheat (Zhang *et al*., 2022).

Overall, the trend of strong positive correlations among growth and yield traits indicates that synchronized nitrogen supply through appropriate scheduling of prilled and nano-urea enhanced growth parameters and yield attributes simultaneously. Efficient nitrogen management is known to improve nitrogen uptake, utilization efficiency and ultimately grain yield (Fageria and Balgir, 2005 ; Ladha *et al.*, 2005). These findings confirm that better nitrogen scheduling improves interrelationships among growth and yield traits, leading to higher productivity.

Despite these promising results, the study was conducted for a single season under (Vertisol), which may limit its wider applicability. Further, multi-location and long term studies are required to validate the sustainability of nano-urea based nitrogen management and to assess its economic feasibility.

Overall, the findings demonstrate that the use of prilled urea along with nano-urea sustains wheat productivity, offering a viable and sustainable alternative to conventional nitrogen fertilization.

Regression analysis

Relationship between grain yield and straw yield

The strong linear relationship between straw yield and grain yield indicates a close linkage through total biomass production and assimilates portioning, commonly described by the harvest index. The near 1:1 increase suggests that additional vegetative biomass is efficiently converted into grain yield. This finding is consistent with earlier studies by Donald 1963 and Hay 1995, who highlighted the importance of biomass accumulation and its allocation to reproductive parts in determining yield. High R^2 value reflects low variability among observations, likely due to uniform growing conditions and management. Similar strong relationships have been reported under optimal environments where growth limiting factors are minimal (Sinclair and Muchow, 1999). The negative intercept is mainly a statistical outcome and has limited biological significance (Steel and Torrie, 1980). Overall the result suggests that straw yield can be reliable indicator of grain yield under split application of urea and foliar spray of nano-urea, supporting findings from previous cereal yield studies (Fischer, 2008).

Relationship between grain yield and test weight

The strong positive relationship between test weight and grain yield indicates that improved garin filling and kernel density contribute substantially to yield formation, also well filled grains enhance both mass and productivity (Darby and Lauer, 2002). Test weight is widely recognized as an indicator of grain quality and is often positively associated with kernel weight and overall yield in cereal crops due to efficient assimilate portioning during grain filling (Blum, 2011). However, test weight alone does not fully determine yield, since grain yield is a complex trait influenced by kernel number, genotype and environmental conditions. Under stress environments, the relationship between test weight and grain yield weakens (Sareen *et al*., 2018).

Relationship between grain yield and grains per earhead

The strong positive association between grains per earhead and grain yield highlights the importance of grain number as a key yield determining component, as increase in grain number directly enhance final productivity (Fischer, 1985). Grain number per earhead is often considered the most critical determinant of yield in cereals because it reflects successful flowering, pollination and early grain set (Slafer, 2003). High R^2 value observed in this study suggests that grains per earhead is a reliable predictor of yield under the given conditions. However, grain yield is a complex trait influenced by interactions among grain number, grain weightg and environmental factors. Under stress conditions, compensatory effects between grain number and grain size may occur, potentially weakening this relationship (Reynolds *et al*., 2009).

Principal component analysis (PCA) of yield attributes

The results of PCA indicated that a major proportion of variability was explained by the PC1, suggesting a strong interrelationship among yield and yield attributing traits. The positive clustering of grain yield with grains per earhead, ear length, straw yield and harvest index suggests that these traits collectively contribute to yield improvement. Similar findings have been reported by Jolliffe (2002), who emphasized that closely aligned variables in PCA indicate strong correlation and shared variability.

The minor contribution of PC2 and slight deviation of test weight towards this axis indicate that test weight behaves relatively independently compared to other traits. This observation is consistent with findings of Yan and Kang (2003), who reported that traits deviating from the main axis represent independent source of variation.

The strong positive association among yield attributes observed in the present study corroborates earlier reports by Mohammadi and Prasanna (2003), who highlighted that yield is a complex trait governed by multiple interrelated components. Therefore simultaneous improvement of these traits can lead to enhanced productivity. The present findings suggest that grains per earhead, ear length and straw yield can be considered reliable selection criteria for yield improvement, as they are closely associated an dcontribute significantly to overall variability.

Conclusion

The study clearly demonstrates that integration of nano-urea with reduced levels of conventional nitrogen fertilizer is an effective strategy for sustaining wheat productivity. Application of 50% RDN supplemented with nano-urea sprays at critical growth stages produced yield statistically comparable to 100% RDF, indicating the possibility of reducing chemical nitrogen input by half. This approach minimizes environmental risks associated with excessive nitrogen application. Therefore, the combined use of prilled and nano-urea can be recommended as a sustainable and economically viable alternative for improving nutrient management in wheat under Vertisol conditions.

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