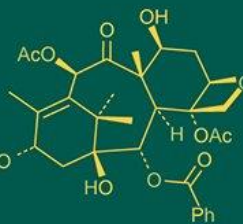
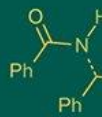
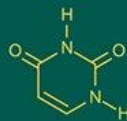
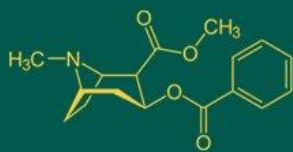


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Evaluating the combined impact of nano-urea and FYM on pearl millet performance in South Haryana's semi-arid agro-ecosystem

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Abstract

A two-year field study was conducted during the *kharif* seasons of 2023 and 2024 at the Agronomy Research Farm, SGT University, Gurugram, Haryana, to investigate the interactive effects of integrated nutrient management strategies on the growth and biomass production of three pearl millet cultivars. The experimental design was laid out in factorial randomized block with three replications, evaluating three cultivars (Pioneer 86m90, HHB 299, MPMH 21) against seven nutrient treatments: T₁ (Control), T₂ (100% RDN through FYM), T₃ (50% RDN through FYM + 2 foliar sprays of nano-urea), T₄ (100% RDN through chemical fertilizer), T₅ (50% RDN through chemical fertilizer + 2 foliar sprays of nano-urea), T₆ (75% RDN through chemical fertilizer + 2 foliar sprays of nano-urea) and T₇ (75% RDN through FYM + 2 foliar sprays of nano-urea). The results demonstrated that both cultivar genetics and nutrient management significantly influenced growth parameters and dry matter accumulation over both the experimental years. The cultivar Pioneer 86m90 consistently exhibited superior performance, recording the maximum plant height (26.4, 143.4 and 173.6 cm in 2023 and 27.8, 144.7 and 174.8 cm in 2024 at 30, 60 DAS and at harvest) respectively and dry matter accumulation (232.92 g/plant in 2023 and 239.28 g/plant in 2024 at 30, 60 DAS and harvest). Among the nutrient treatments, T₆ emerged as the most effective, producing the tallest plants and highest biomass across both years, significantly outperforming the full-dose chemical fertilizer treatment (T₄). The results demonstrated the efficacy of combining reduced chemical nitrogen with nano-urea foliar sprays in enhancing nitrogen use efficiency and sustaining crop growth. The treatment T₇ also performed well and results revealed that the potential of integrating organic manures with nano-fertilizer. The study concluded that the application of 75% of the recommended nitrogen dose through chemical fertilizers with two foliar sprays of nano-urea, in conjunction with the high-yielding cultivar Pioneer 86m90, constitutes an optimal strategy for maximizing pearl millet productivity in the semi-arid regions of Southern Haryana.

Keywords: Pearl millet, nano-urea, farmyard manure, plant height, dry matter accumulation

Introduction

Pearl millet (*Pennisetum glaucum* L.) is enormously important for food security in dry (arid and semi-arid) parts of Africa and Asia. It is especially valuable because it is very tolerant to drought and high temperatures (Yadav and Rai, 2013) [7]. Being a C₄ plant, it can photosynthesise more efficiently under strong sunlight and with less water-this helps it grow better than many other crops in harsh climates.

In India, pearl millet is a key staple crop, particularly in states like Haryana, where it's mainly grown during the *kharif* season (monsoon crop). But its yield (productivity) is often held back by poor soil fertility in these regions. In southern Haryana, soils are usually sandy loam, slightly alkaline, low in organic matter and nitrogen, and have only moderate levels of phosphorus and potassium (Yadav *et al.*, 2022) [8]. Because nitrogen is often lacking, the plants can't fully realize their genetic potential.

Farmers typically use chemical nitrogen fertilizers (especially urea) to supply nitrogen. However, much of the nitrogen in urea is volatilized, only 30-40% is taken up by the plant-which leads to both economic loss and environmental harm (*e.g.* groundwater contamination, greenhouse gas emissions).

To overcome this, researchers are promoting Integrated Nutrient Management (INM)-combining organic and inorganic nutrient sources.

One common organic source is farmyard manure (FYM). FYM helps by improving soil structure, increasing water retention, and gradually releasing nutrients. Over time it helps make soils more fertile and resilient.

Meanwhile, nanotechnology offers a novel tool: nano-urea. When the nitrogen particles are reduced to the nanoscale, they can be taken up more efficiently by plants (for example via leaves) and thus increase nitrogen use efficiency (NUE) (Subramanian *et al.*, 2021) [6]. Because nano-urea delivers nitrogen more efficiently, less fertilizer may be needed, and losses to the environment can be reduced.

Thus, your proposed study-to test how combining FYM and nano-urea works on different pearl millet cultivars across seasons-is timely. It aims to find whether these two approaches can work together (synergistically) to boost growth, improve nitrogen uptake, and overcome the soil fertility limits in challenging environments.

Materials and Methods

The investigation was carried out during the *kharif* seasons of 2023 and 2024 at the Agronomy Research Farm of the Faculty of Agricultural Sciences, SGT University, located in Gurugram, Haryana. The geographical coordinates of the experimental site are 28°N latitude and 77°E longitude, with an elevation of 217 meters above mean sea level, positioning it within the semi-arid subtropical zone characteristic of southern Haryana. This region is characterized by extreme climatic variations, featuring intensely hot and dry summers and relatively cold winters. The monsoon is the major source of moisture, with total seasonal precipitation recorded at 615 mm in 2023 and a slightly higher 692 mm in 2024, the majority of which (80-88%) was concentrated between July and September. Temperature regimes during the cropping period initiated with maxima often ranging between 35 and 43 °C, gradually declining as the season progressed towards the crop's reproductive phase in September. Before the initiation of the experiment, initial soil sampling from a depth of 0-15 cm revealed that the soil was sandy loam in texture, comprising 62.71% sand, 19.84% silt, and 17.45% clay. The soil reaction was slightly alkaline (pH 7.89) with low electrical conductivity (0.84 dS/m), classifying it as non-saline. Remarkably, the soil was characterized by low inherent fertility, with poor organic carbon status (0.29%) and low available nitrogen (147.45 kg/ha), medium range of available phosphorus (19.12 kg/ha) and medium to high range of potassium (245 kg/ha) reported after analysis of the soil sample. The study was laid out under a Factorial Randomized Block Design (RBD), a statistical design ideally suited for evaluating the main effects of multiple factors and their interactions. The experiment has two factors: cultivars and nutrient management practices. The first factor consisted of three high-yielding pearl millet hybrids: V₁ (Pioneer 86m90), V₂ (HHB 299) and V₃ (MPMH 21). The second factor comprised of seven different nutrient management treatments, designed to compare conventional and integrated approaches: T₁ served as an absolute control with no fertilizer application; T₂ provided 100% of the Recommended Dose of Nitrogen (RDN) solely through Farmyard Manure (FYM), T₃ involved 50% RDN through FYM combined with two foliar sprays (FS) of nano-urea, T₄ represented the conventional practice of applying 100% RDN through chemical fertilizer, T₅ consisted of 50% RDN through

chemical fertilizer plus two FS of nano-urea T₆ involved 75% RDN through chemical fertilizer plus two FS of nano-urea and T₇ provided 75% RDN through FYM plus two FS of nano urea. The combination of three cultivars and seven treatments generated 21 treatment combinations, each replicated three times, resulting in a total of 63 experimental plots. Each plot was demarcated with a gross size of 4.5 m x 3.0 m, while a net plot area of 3.0 m x 1.8 m was meticulously maintained for data collection to exclude border effects. The crop was established using a seed rate of 5.0 kg/ha, with seeds sown at a spacing of 45 cm between rows and 15 cm between plants.

All agronomic practices, including land preparation, sowing, and irrigation, were executed uniformly across all plots in accordance with the standard package of practices recommended for the region by CCS Haryana Agricultural University, Hisar, to ensure that the observed effects were attributable solely to the imposed treatments. For the assessment of growth parameters, plant height was measured from the base of the plant to the tip of the longest leaf at critical phenological stages: 30, 60 DAS and at harvest. This measurement was performed on three randomly tagged plants within the net plot area of each replication. To quantify biomass production, dry matter accumulation was determined by carefully uprooting three representative plants from each net plot at the same growth stages. These plant samples were first sun-dried to remove surface moisture and placed in a hot-air oven maintained at 60 ± 5 °C until a constant weight was achieved, final dry weight was recorded in grams per plant. The collection of this data over two consecutive years ensured the reliability and validity of the results. All recorded data were subjected to rigorous statistical scrutiny through analysis of variance (ANOVA) appropriate for the factorial RBD, using the OPSTAT software platform. The significance of differences among treatment means was adjudged at the 5% probability level ($p \leq 0.05$) using the Critical Difference (C.D.) test, providing a robust foundation for interpreting the effects of the experimental factors.

Results and Discussion

Plant Height

Plant height, a key morphological attribute, reflects the vegetative growth potential and adaptability of a crop to environmental and management conditions. In the present study, analysis of variance revealed that plant height was significantly influenced by genotype and nutrient management practices, and their interactive effects, highlighting the role of genotype × environment interaction in determining growth performance (Yadav and Rai, 2013) [7]. Detailed assessment of the data showed a significant variation among the cultivars. The hybrid Pioneer 86m90 (V₁) consistently and markedly outperformed the other genotypes, confirming its vigorous growth habit throughout the crop growth period. During the 2023 and 2024 *kharif* seasons, the plant heights recorded were 26.4 and 27.8 cm at 30 DAS, 143.4 and 144.7 cm at 60 DAS, and 173.6 and 174.8 cm at harvest, respectively. The significant increase in plant height was recorded during 2024 as compared to 2023. This consistent dominance can be attributed to its inherent genetic blueprint, which likely encodes for more efficient hormonal regulation, cell elongation processes, and a superior capacity for resource capture and utilization, as noted in other high-performing cereal hybrids (Gupta *et al.*,

2015) [2]. The cultivars HHB 299 (V₂) and MPMH 21 (V₃) followed in descending order, confirming the significant role of varietal selection in determining the crop's architectural framework.

The nutrient management treatment also showed a positive influence on different treatments. The results were presented in Table 1, comparing the nutrient-treated plots and the control (T₁), which consistently showed the most stunted growth, underscoring the acute nitrogen deficiency of the experimental soil and the crop's high demand for this macronutrient. The most prominent finding was the exceptional performance of the integrated treatment T₆ (75% RDN through chemical fertilizer + 2 foliar sprays of nano-urea). This treatment consistently produced the tallest plants with plant heights of 170.9 cm and 172.2 cm at harvest respectively, during 2023 and 2024. Its supremacy over the

conventional practice of T₄ (100% RDN through chemical fertilizer), which yielded 169.4 and 170.6 cm in the respective years. This demonstrates that a 25% reduction in soil-applied urea can be more than compensated for by the targeted application of nano-urea. The physiological rationale is compelling: the basal chemical fertilizer provides a readily available nitrogen pool for foundational growth, while the foliar-applied nano urea, with its nano scale particle size and high surface area, offers a highly efficient supplemental nitrogen source during peak vegetative and reproductive demand periods. This leads to enhanced photosynthetic activity, prolonged leaf longevity, and uninterrupted growth, thereby optimizing the plant's developmental trajectory (Subramanian *et al.*, 2021; Liu *et al.*, 2023) [6, 3].

Table 1: Effect of different cultivars and nutrient management treatments on plant height (cm) of pearl millet

Treatments	Days after sowing					
	30		60		at harvest	
	2023	2024	2023	2024	2023	2024
Cultivars						
V ₁ -Pioneer 86m90	26.4	27.8	143.4	144.7	173.6	174.8
V ₂ -HHB 299	23.2	24.6	138.7	139.9	168.4	169.6
V ₃ -MPMH 21	22.2	23.5	136.5	137.5	163.9	165.1
SE(m) ±	0.40	0.45	1.03	1.08	1.37	1.41
C.D.(P = 0.05)	1.20	1.35	3.09	3.24	4.15	4.23
Nutrient management treatments						
T ₁ -Control	19.4	20.2	130.8	132.6	161.7	163.1
T ₂ -100% RDN through FYM	24.3	25.5	140.6	141.6	168.2	169.7
T ₃ -50% RDN through FYM + 2 FS of Nano urea	22.9	24.1	138.4	139.5	167.5	168.7
T ₄ -100% RDN through chemical fertilizer	25.0	26.1	141.5	142.6	169.4	170.6
T ₅ -50% RDN through chemical fertilizer + 2 FS of Nano urea	23.8	24.7	139.5	140.6	167.9	169.1
T ₆ -75% RDN through chemical fertilizer + 2 FS of Nano urea	26.4	27.6	143.3	144.4	170.9	172.2
T ₇ -75% RDN through FYM + 2 FS of Nano urea	25.7	26.8	142.4	143.5	170.2	171.4
SE(m) ±	0.36	0.40	0.99	1.02	1.27	1.32
C.D. (P = 0.05)	1.08	1.22	2.97	3.03	3.75	3.96
Interaction effect of different cultivars and nutrient management treatments (V X T)						
SE(m) ±	0.28	0.36	1.00	1.01	1.20	1.24
C.D. (P = 0.05)	0.89	1.08	3.02	3.03	3.64	3.70

The compelling efficacy of T₇ (i.e. 75% of recommended nitrogen via FYM plus two foliar sprays of nano-urea) underlines its promise as a more sustainable intensification pathway. Although its effect was marginally inferior to that of T₆, statistically it was comparable and markedly superior to the control and other low-dose nutrient management treatments. This outcome implies that FYM contributes not just nutrients, but also enhances soil organic carbon and fosters a healthier rhizosphere environment. Such improvement in soil physical, chemical, and biological properties allows FYM to act as a slow-release nutrient base that complements the rapid, targeted nitrogen supply from foliar nano-urea, in line with integrated soil fertility management principles (Mäder *et al.*, 2002) [4]. The significant genotype × treatment interaction further reinforces that the greatest phenotypic expression (e.g. in plant height) arises not from additive effects of genotype and treatment alone, but from genuine synergistic interactions; an illustrative example is the V₁ × T₆ combination yielding ~175.88 cm in 2023. This genotype-management specificity underscores the importance of tailoring nutrient regimes to particular cultivars if we aim to close yield gaps and move toward precision agriculture (Sharma *et al.*, 2021) [5].

Dry Matter accumulation

Dry matter accumulation (DMA) provides an integrative measure of photosynthetic gain minus respiratory losses, and it supports final yield. In our study, Dry matter accumulation in pearl millet follows a classic “sigmoidal” growth curve: during the early stage growth is slow and gradual, then between 30 and 60 DAS (days after sowing) the accumulation accelerates sharply, and finally as the plant nears maturity the increase slows down and plateaus. This pattern reflects how the balance shifts over time between the source (which produce sugars via photosynthesis) and the sink (which consume or store those sugars). Consistent with its superior plant height, the hybrid Pioneer 86m90 (V₁) also demonstrated the highest dry matter accumulation (DMA) among the tested cultivars. At harvest, its dry matter accumulation reached 232.92 g/plant in 2023 and 239.28 g/plant in 2024, significantly surpassing those of V₂ and V₃. This enhanced performance suggests that V₁ not only achieved greater stature but also exhibited improved efficiency in light interception and carbon assimilation. These advantages are likely attributed to a more favourable canopy structure and superior photosynthetic capacity per unit leaf area, which are characteristic of high-performing hybrids like Pioneer 86m90.

Nutrient management significantly influenced dry matter accumulation (DMA) in pearl millet. The control treatment (T₁), which lacked nitrogen supplementation, resulted in the lowest dry matter accumulation having 188.79 g/plant in 2023 and 198.42 g/plant in 2024—highlighting the essential role of nitrogen in promoting photosynthesis and vegetative growth. In contrast, the integrated nutrient management treatment T₆, comprising 75% of the recommended nitrogen dose through chemical fertilizer combined with two foliar sprays of nano-urea, achieved the highest DMA at all growth stages. At harvest, T₆ recorded 213.66 g/plant in 2023 and 221.64 g/plant in 2024. This superior performance is attributed to T₆'s ability to maintain a consistent and adequate nitrogen supply throughout the crop's lifecycle, thereby sustaining photosynthetic efficiency and promoting continuous biomass accumulation.

The application of basal chemical fertilizers ensures that pearl millet avoids early-season nitrogen stress, which is crucial for tillering and canopy establishment. Foliar sprays of nano-urea serve as a "booster" during the period of maximum growth (30-60 DAS), countering the nitrogen dilution effect and supporting the high metabolic demands

of rapid cell division and expansion. This results in larger stems, more numerous and larger leaves, and a greater total photosynthetic ability, thereby channelling more assimilates toward biomass production. Notably, the treatment T₆ (75% RDN through chemical fertilizer + two foliar sprays of nano-urea) outperformed T₄ (100% RDN through chemical fertilizer), despite using less total soil-applied nitrogen, highlighting the enhanced nitrogen use efficiency (NUE) afforded by nanotechnology.

Genotype × Nutrient Management Interaction

The significant interaction for dry matter accumulation (DMA), particularly evident in the 2024 data, provides convincing evidence of the combination of the high-performing hybrid Pioneer 86m90 (V₁) and the integrated nutrient management treatment T₆ achieved a dry matter accumulation of 243.9 g/plant, the highest in the study. This suggests that the genetic potential of Pioneer 86m90 for high biomass is fully realized only when paired with a nutrient regime that supplies nitrogen in a sustained and efficient manner. Thus, synergy between a responsive genotype and a precision nutrient strategy is central to maximizing productivity in pearl millet systems.

Table 2: Effect of different cultivars and nutrient management treatments on dry matter accumulation (g/plant) of pearl millet

Treatments	Days after sowing					
	30		60		at harvest	
	2023	2024	2023	2024	2023	2024
Cultivars						
V ₁ -Pioneer 86m90	9.69	10.80	99.04	100.59	232.92	239.28
V ₂ -HHB 299	6.61	7.27	93.57	94.77	206.04	212.10
V ₃ -MPMH 21	5.61	6.28	90.54	91.74	183.12	189.75
SE(m) ±	0.11	0.15	1.02	1.06	2.01	2.08
C.D. (P = 0.05)	0.32	0.45	3.09	3.18	6.05	6.25
Treatments						
T ₁ -Control	5.96	6.88	90.92	92.13	188.79	198.42
T ₂ -100% RDN through FYM	7.22	8.01	94.74	95.95	211.98	217.59
T ₃ -50% RDN through FYM + 2 FS of Nano urea	6.23	7.08	93.32	94.51	204.84	210.15
T ₄ -100% RDN through chemical fertilizer	7.82	8.61	95.49	96.68	211.47	216.81
T ₅ -50% RDN through chemical fertilizer + 2 FS of Nano urea	6.76	7.54	93.79	95.00	206.79	212.07
T ₆ -75% RDN through chemical fertilizer + 2 FS of Nano urea	8.86	9.69	97.10	98.28	213.66	221.64
T ₇ -75% RDN through FYM + 2 FS of Nano urea	8.17	9.01	96.15	97.36	212.94	221.10
SE(m) ±	0.07	0.12	0.95	0.97	1.90	1.95
C.D. (P = 0.05)	0.21	0.36	2.88	2.91	5.67	5.83
Interaction effect of different cultivars and nutrient management treatments						
SE(m) ±	0.05	-	0.90	0.92	-	1.89
C.D. (P = 0.05)	0.17	NS	2.70	2.76	NS	5.67

Conclusion

This study highlights the importance of integrating advanced nutrient management practices with high-performing cultivars to enhance productivity in pearl millet. The combination of Pioneer 86m90 with the T₆ nutrient regime offers a promising approach for sustainable intensification in semi-arid agro-ecosystems. Future research should focus on evaluating the long-term effects on soil health, economic viability, and consistency of response across diverse agro-climatic conditions.

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