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Impact of Nano Urea on Quality, Plant and Soil Nutrients Status of Pearl Millet (*Pennisetum glaucum* Br.) under Precision Nitrogen Management

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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 summer seasons of 2022 and 2023 at the Pearl Millet Research Station, Junagadh Agricultural University, Jamnagar, Gujarat, India, to assess the influence of nano urea on the quality parameters, nutrient uptake, and soil nutrient status of pearl millet under precision nitrogen management. The study was arranged in a randomized block design consisting of ten treatment combinations with three replications, and the experiment was carried out

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on medium black calcareous soil. The findings revealed that the treatment receiving 40 kg as basal, 40 kg N through urea at 25–30 DAS, and 2 foliar sprays of nano urea (0.4%) when the LCC value was ≤ 4 resulted in the highest nitrogen and phosphorus contents in grain (1.650% and 0.342%) and fodder (0.730% and 0.178%), respectively. This treatment also showed superior nutrient uptake, with nitrogen, phosphorus, and potassium uptake by grain and fodder recorded at 77.36% and 63.28%, 16.07% and 15.47%, and 25.87% and 67.83%, respectively. Furthermore, it maintained higher available nitrogen in the soil after harvest (299.34 kg/ha) compared to other treatments.

Keywords: Pearl millet; Leaf colour chart (LCC); nano urea; nutrient content and uptake.

1. INTRODUCTION

“Pearl millet stands out among cereal crops because of its distinctive physiological and agronomic features. Being a C_4 species, it utilizes light and carbon dioxide more efficiently, resulting in greater photosynthetic activity and biomass production. This crop is well adapted to harsh and variable environments, performing reliably even in regions where maize and sorghum often fail to produce viable yields. Owing to its resilience, pearl millet significantly contributes to both food and nutritional security. It matures early, withstands drought conditions effectively, requires limited external inputs, and exhibits strong resistance to various biotic and abiotic stresses” (Project Coordinator Review, 2021).

“Pearl millet is recognized for its exceptional nutritional and health-promoting properties, making it particularly beneficial for individuals affected by lifestyle-related disorders such as diabetes and obesity. Compared to other staple cereals like wheat, rice, maize, and sorghum, it possesses a richer nutritional profile. The grain contains higher levels of fibre, minerals, and bioactive compounds, which aid in maintaining healthy blood sugar levels, improving digestion, and supporting overall metabolic health” (Arya et al., 2022). “Pearl millet grain contains 9-15 per cent protein, 5-6 per cent carbohydrates and 1-2 per cent minerals and high densities of iron, zinc and more balanced amino acid profile and also rich in vitamins, thiamine and riboflavin content than maize and sorghum” (Chaudhari et al., 2018). “In Gujarat, pearl millet plays a vital role in the state’s agriculture, ranking next to wheat in area and following wheat and rice in total production. Farmers grow this crop during the kharif, pre-rabi, and summer seasons, but in recent years, the cultivation area during summer has been steadily rising. This trend is mainly because farmers have a short interval after rabi crop harvest, along with the increasing need for green fodder and the favorable climatic conditions during summer” (Muchhadiya et al., 2024). “Compared to the kharif season, summer pearl millet generally achieves higher productivity owing to the availability of assured irrigation and warm temperatures that favor better crop growth. As a result, pearl millet grown in the summer season absorbs and utilizes more nutrients efficiently from the soil and fertilizers” (Muchhadiya et al., 2024).

“Pearl millet demands relatively higher amounts of nutrients for optimal growth and yield. When the crop does not receive sufficient fertilizers, it often results in poor productivity and lower economic returns compared to well-fertilized fields. Among the essential nutrients, nitrogen is commonly the most deficient in many soils. To maximize yield potential, it is important to manage nitrogen efficiently by understanding how soil properties, plant needs, and environmental conditions interact to improve nutrient absorption and utilization” (Sharma et al., 2022). “Nitrogen use efficiency in cereal crops remains quite low, with an average value of about 21%. This inefficiency largely results from improper scheduling and distribution of nitrogen doses, as well as the application of fertilizer in quantities greater than what the crop actually requires. Applying a uniform fertilizer recommendation across different fields often leads to poor nutrient use efficiency because soil nitrogen content varies widely from field to field. Hence, to improve productivity and reduce nitrogen losses, adopting site-specific and crop-based nitrogen management practices using decision-support tools like the Leaf Color Chart (LCC) can be highly effective. Such approaches help optimize fertilizer use, minimize wastage, and lower production costs” (Muchhadiya et al., 2024).

“Urea is the most widely used nitrogen fertilizer, contributing nearly 82% of the total nitrogen applied to crops across the world, with around

188 million metric tonnes used each year. The continuous and excessive use of chemical fertilizers has disturbed the balance of the NPK ratio in soils. Since the nitrogen use efficiency of urea is only about 30–40%, a significant portion of it is lost to the environment, adversely affecting soil fertility, air quality, and water resources. Overuse of urea also makes crops more prone to pest and disease attacks and can cause lodging problems. Nano-fertilizers, on the other hand, have the ability to release nutrients slowly and uniformly for over 30 days, which helps enhance nutrient use efficiency while reducing harmful environmental impacts" (Kannoj et al., 2022). Nano Urea Liquid is an eco-friendly and advanced fertilizer designed to enhance nutrient use efficiency while promoting sustainable agriculture. It offers a long-term solution to environmental pollution and climate change by reducing nitrous oxide emissions and preventing contamination of soil, air, and water resources. In addition to being cost-effective compared to conventional urea, nano fertilizers represent an innovative approach to nutrient management and conservation. Nano urea, in particular, has emerged as a sustainable and environmentally responsible alternative to traditional bulk nitrogen fertilizers. The present study aims to develop real-time nitrogen management technologies and enhance farmers' understanding of efficient nitrogen utilization. Ultimately, the goal is to improve nitrogen use efficiency and achieve higher crop productivity in a sustainable manner.

2. MATERIALS AND METHODS

A field investigation was undertaken at the Pearl Millet Research Station of Junagadh Agricultural University, Jamnagar, Gujarat, during the consecutive summer seasons of 2022 and 2023 to assess the impact of nano urea on the quality traits, nutrient uptake, and soil nutrient status of pearl millet under precision nitrogen management practices. The soil of the experimental plot was clayey in texture (in both the years), low in organic carbon (0.39 and 0.43 %), slightly alkaline in reaction with pH (8.40 and 8.35) and EC (0.37 and 0.43 dS/m) in 2022 and 2023, respectively. The soil was medium in available nitrogen (261 and 268 kg/ha), medium in available phosphorus (35.4 and 38.7 kg/ha) and higher in available potash (310 and 316 kg/ha) in 2022 and 2023, respectively.

The experiment was laid out with 10 treatment combinations comprising in a randomized block design with three replications *viz*., T_1 (40 kg N as basal + 40 kg N through urea at 25-30 DAS + 40 kg N through urea at 40-45 DAS), T_2 (40 kg N as basal + 40 kg N through urea at 25-30 DAS + 2 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_3 (40 kg N as basal + 30 kg N through urea at 25-30 DAS + 3 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_4 (40 kg N as basal + 20 kg N through urea at 25-30 DAS + 4 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_5 (40 kg N as basal + 20 kg N through urea at 25-30 DAS + 3 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_6 (40 kg N as basal + 10 kg N through urea at 25-30 DAS + 4 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_7 (40 kg N as basal + 10 kg N through urea at 25-30 DAS + 3 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_8 (40 kg N as basal + 4 foliar sprays of nano urea 0.4% when LCC ≤ 4), T_9 (40 kg N as basal + 3 foliar sprays of nano urea 0.4% when LCC ≤ 4) and T_{10} (control). Quantity of soil applied fertilizer and foliar application of nano urea for each plot as per treatments. Soil applied nitrogen was applied in three equal splits *i.e.* basal, 25-30 DAS and at 40-45 DAS from DAP, Urea fertilizers and foliar spray of nano urea as per treatment.

The six-panel Leaf Colour Chart (LCC) used in the study was obtained from Nitrogen Parameters, Chennai, which produces LCCs following the specifications and design prototype of the International Rice Research Institute (IRRI) (http://nitrogenparameters.com/irri.html). To ensure accuracy and consistency, LCC readings were recorded following a uniform procedure. From 15 days after sowing (DAS) onward, readings were taken from five randomly selected plants in each treatment plot. The topmost fully expanded and healthy leaf of each tagged plant was used for observation. The colour of the leaf was compared with the shades on the LCC to determine its value, and the average score was calculated for each plot. During observation, the central portion of the leaf was placed on the colour strips of the chart without detaching it from the plant. All readings were consistently taken between 8:00 and 10:00 a.m. to avoid variation due to light intensity. The LCC was kept away from direct sunlight while recording the readings and the same person took all observations from start to finish minimizing subjective bias and maintaining uniformity in data collection.

All these statistical estimates were computed by standard statistical procedure (Panse and Sukhatme, 1985).

3. RESULTS AND DISCUSSION

3.1 Protein Content

Among the different real-time nitrogen management practices tested (Table 1), the treatment that received 40 kg N as a basal dose along with 40 kg N through urea at 25–30 DAS and 2 foliar sprays of nano urea (0.4%) whenever the Leaf Colour Chart (LCC) reading was ≤ 4 (T_2) recorded the highest protein content of 10.32% in pearl millet grain. This was followed by the treatment T_3, which involved 40 kg N as a basal application, 30 kg N through urea at 25–30 DAS, and 3 foliar sprays of nano urea (0.4%) when LCC ≤ 4. The next treatment in order of effectiveness was T_1, which received 40 kg N as basal, 40 kg N ha^{-1} through urea at 25–30 DAS, and another 40 kg N through urea at 40–45 DAS. Slightly lower protein content was observed in T_4, where 40 kg N was applied as basal with 20 kg N through urea at 25–30 DAS and 4 sprays of nano urea (0.4%) when LCC ≤ 4. These findings suggest that a balanced combination of soil-applied nitrogen and foliar sprays of nano urea enhances nitrogen utilization efficiency, leading to improved protein accumulation in pearl millet grain.

The observed improvement could be linked to the use of nano urea under real-time nitrogen management practices. Due to its very small particle size and large surface area, nano urea can easily penetrate plant tissues and move within different parts of the plant. This efficient absorption enhances nitrogen uptake and increases the overall nitrogen concentration in plant tissues, ultimately leading to higher protein accumulation. Similar results were also reported by Manikandan and Subramanian (2016), Barkha Rani et al*.* (2019), Tarafder et al*.* (2019), Maurya et al*.* (2022) and Patel et al*.* (2024) were in supporting the present investigation.

3.2 Nutrient Content in Grain and Fodder

The results summarized in Tables 2 and 3 showed that applying 40 kg N as a basal dose along with 40 kg N through urea at 25–30 DAS and 2 foliar sprays of nano urea (0.4%) whenever the LCC reading was ≤ 4 (T_2) led to noticeably higher nitrogen and phosphorus contents in both grain and fodder of pearl millet. The recorded values were 1.650% nitrogen and 0.342% phosphorus in grain, and 0.730% nitrogen and 0.178% phosphorus in fodder. This treatment performed on par with T_3, which included 40 kg N as basal + 30 kg N through urea at 25–30 DAS along with 3 nano urea sprays, and T_1, which received 40 kg N as basal + 40 kg N through urea at 25–30 DAS and another 40 kg N through urea at 40–45 DAS. In contrast, potassium concentration in both grain and fodder was not significantly affected by any of the nutrient management treatments.

The positive effect of LCC-based foliar spraying of nano urea, along with soil-applied nitrogen, on nutrient content in pearl millet may be due to the improved nutrient availability in both the root zone and the plant system. A higher concentration of nitrogen around the roots, together with enhanced cellular metabolic activity, likely promoted greater absorption and accumulation of nutrients in the vegetative parts of the crop. This increased nutrient buildup in vegetative tissues supported better translocation of nutrients to the reproductive structures, which ultimately led to higher nutrient concentrations in both grain and straw. These results were in accordance with the findings of Barad et al. (2018), Lahari et al. (2021), Kannoj et al*.* (2022), Sahu et al*.* (2022a) and Sharma et al. (2022).

3.3 Nutrient Uptake in Grain and Fodder

The observations summarized in Tables 4 and 5 showed that the treatment consisting of 40 kg N as a basal dose, 40 kg N through urea at 25–30 DAS, and 2 foliar sprays of nano urea (0.4%) when the LCC reading was ≤ 4 (T_2) resulted in the highest uptake of nitrogen, phosphorus, and potassium by both grain and fodder of pearl millet. Under this treatment, nitrogen uptake was 77.36% in grain and 63.28% in fodder, while phosphorus uptake was 16.07% and 15.47%, and potassium uptake was 25.87% and 67.83%, respectively. These results were statistically similar to those obtained with T_3, which included 40 kg N as basal + 30 kg N through urea at 25–30 DAS with 3 foliar sprays of nano urea (0.4%) when LCC ≤ 4, and T_1, which involved 40 kg N as basal + 40 kg N through urea at 25–30 DAS and another 40 kg N through urea at 40–45 DAS. The findings suggest that combining soil-applied nitrogen with foliar applications of nano urea enhances nutrient absorption efficiency, leading to greater nutrient uptake and improved crop performance in pearl millet under precision nitrogen management.

Table 1. Effect of precision nitrogen management on protein content of pearl millet

Treatments	Protein content (%)		
	2022	**2023**	**Pooled**
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	10.09	10.14	10.12
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	10.29	10.35	10.32
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	10.19	10.27	10.23
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.84	9.89	9.87
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.64	9.71	9.68
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.40	9.44	9.42
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.39	9.41	9.40
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.31	9.37	9.34
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	9.30	9.35	9.33
T_{10} : Control (without N application)	8.15	8.20	8.18
SEm±	0.29	0.28	0.20
C.D. at 5%	0.87	0.84	0.59
C.V. %	5.33	5.11	5.22
Y × T			
SEm± 0.29			
C.D. at 5% NS			

Table 2. Effect of precision nitrogen management on nitrogen, phosphorus and potassium contents in grain of pearl millet

Treatments	Nitrogen content in grain (%)			Phosphorus content in grain (%)			Potassium content in grain (%)		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	1.615	1.622	1.618	0.324	0.332	0.328	0.536	0.540	0.538
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.646	1.655	1.650	0.338	0.346	0.342	0.547	0.551	0.549
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.631	1.644	1.637	0.330	0.337	0.333	0.541	0.545	0.543
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.575	1.583	1.579	0.318	0.324	0.321	0.533	0.536	0.534
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.543	1.554	1.548	0.310	0.317	0.313	0.524	0.527	0.525
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.504	1.510	1.507	0.302	0.308	0.305	0.524	0.525	0.524
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.502	1.506	1.504	0.295	0.300	0.297	0.519	0.522	0.520
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.490	1.499	1.494	0.289	0.293	0.291	0.517	0.520	0.518
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	1.489	1.496	1.492	0.280	0.285	0.282	0.511	0.515	0.513
T_{10} : Control (without N application)	1.305	1.313	1.309	0.268	0.273	0.270	0.505	0.507	0.506
SEm±	0.047	0.045	0.033	0.012	0.011	0.008	0.02	0.01	0.01
C.D. at 5%	0.140	0.135	0.094	0.035	0.031	0.022	NS	NS	NS
C.V. %	5.33	5.11	5.22	6.55	5.86	6.21	4.97	4.39	4.69
Y × T									
SEm±	0.046			0.011			0.014		
C.D. at 5%	NS			NS			NS		

Table 3. Effect of precision nitrogen management on nitrogen, phosphorus and potassium contents in fodder of pearl millet

Treatments	Nitrogen content in fodder (%)			Phosphorus content in fodder (%)			Potassium content in fodder (%)		
	2022	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	0.693	0.705	0.699	0.163	0.170	0.167	0.763	0.767	0.765
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.726	0.735	0.730	0.174	0.182	0.178	0.776	0.786	0.781
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.704	0.718	0.711	0.166	0.176	0.171	0.769	0.776	0.772
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.676	0.682	0.679	0.160	0.167	0.163	0.755	0.763	0.759
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.673	0.677	0.675	0.157	0.163	0.160	0.745	0.754	0.749
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.665	0.672	0.669	0.155	0.161	0.158	0.740	0.744	0.742
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.662	0.669	0.666	0.153	0.158	0.155	0.735	0.738	0.736
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.647	0.656	0.652	0.150	0.155	0.153	0.730	0.735	0.733
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	0.645	0.650	0.648	0.147	0.151	0.149	0.725	0.730	0.727
T_{10} : Control (without N application)	0.566	0.573	0.570	0.144	0.148	0.146	0.712	0.717	0.714
SEm±	0.020	0.020	0.014	0.005	0.006	0.004	0.020	0.021	0.015
C.D. at 5%	0.058	0.060	0.040	0.016	0.018	0.011	NS	NS	NS
C.V. %	5.07	5.22	5.15	5.71	6.38	6.06	4.68	4.91	4.80
Y × T									
SEm±	0.020			0.06			0.021		
C.D. at 5%	NS			NS			NS		

Table 4. Effect of precision nitrogen management on nitrogen, phosphorus and potassium uptakes in grain of pearl millet

Treatments	Nitrogen uptake in grain (%)			Phosphorus uptake in grain (%)			Potassium uptake in grain (%)		
	2022	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	68.13	70.47	69.30	13.78	14.49	14.14	22.86	23.57	23.21
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	76.69	78.03	77.36	15.80	16.35	16.07	25.54	26.21	25.87
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	70.85	73.49	72.17	14.39	15.14	14.77	23.59	24.55	24.07
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	61.66	63.12	62.39	12.41	13.01	12.71	20.89	21.48	21.19
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	59.65	61.17	60.41	11.99	12.45	12.22	20.25	20.77	20.51
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	58.38	59.17	58.78	11.73	12.09	11.91	20.29	20.48	20.38
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	56.37	57.47	56.92	11.09	11.38	11.24	19.45	19.99	19.72
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	54.70	56.06	55.38	10.66	10.96	10.81	18.96	19.46	19.21
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	52.35	53.74	53.04	9.80	10.22	10.01	17.95	18.53	18.24
T_{10} : Control (without N application)	44.03	45.00	44.51	9.00	9.36	9.18	17.06	17.38	17.22
SEm±	3.90	4.14	2.84	0.78	0.84	0.57	1.25	1.59	1.01
C.D. at 5%	11.57	12.31	8.16	2.32	2.48	1.64	3.72	4.72	2.91
C.V. %	11.19	11.62	11.41	11.20	11.54	11.38	10.49	12.96	11.83
Y × T									
SEm±	4.02			0.81			1.43		
C.D. at 5%	NS			NS			NS		

Table 5. Effect of precision nitrogen management on nitrogen, phosphorus and potassium uptakes in fodder of pearl millet

Treatments	Nitrogen content in fodder (%)			Phosphorus content in fodder (%)			Potassium content in fodder (%)		
	2022	2023	Pooled	2022	2023	Pooled	2022	2023	Pooled
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	57.72	59.51	58.62	13.62	14.32	13.97	63.72	64.98	64.35
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	62.35	64.20	63.28	15.00	15.95	15.47	66.84	68.83	67.83
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	59.07	61.16	60.12	13.95	15.05	14.50	64.58	66.19	65.39
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	54.74	55.58	55.16	13.01	13.58	13.30	61.35	62.46	61.91
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	48.65	51.80	50.23	11.38	12.38	11.88	54.08	57.52	55.80
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	48.33	50.91	49.62	11.26	12.14	11.70	53.70	56.35	55.02
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	46.29	49.24	47.76	10.71	11.63	11.17	51.26	54.35	52.80
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	44.06	45.99	45.03	10.27	10.93	10.60	49.92	51.59	50.75
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	42.14	43.90	43.02	9.63	10.21	9.92	47.52	49.28	48.40
T_{10} : Control (without N application)	35.54	36.73	36.14	9.05	9.49	9.27	44.48	45.97	45.23
SEm±	3.08	2.69	2.05	0.92	0.74	0.59	4.16	3.71	2.78
C.D. at 5%	9.16	8.00	5.88	2.73	2.20	1.69	12.35	11.01	7.99
C.V. %	10.71	8.99	9.85	13.49	10.19	11.85	12.92	11.11	12.02
Y × T									
SEm±	2.90			0.83			3.94		
C.D. at 5%	NS			NS			NS		

Table 6. Effect of precision nitrogen management on available nitrogen, phosphorus and potassium in soil after harvesting of pearl millet

Treatments	Available nitrogen in soil after harvesting (kg/ha)			Available phosphorus in soil after harvesting (kg/ha)			Available potassium in soil after harvesting (kg/ha)		
	2022	**2023**	**Pooled**	**2022**	**2023**	**Pooled**	**2022**	**2023**	**Pooled**
T_1 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 40 kg N through Urea at 40-45 DAS	293.23	305.45	299.34	39.56	41.09	40.32	280.86	281.34	281.10
T_2 : 40 kg N as basal + 40 kg N through Urea at 25-30 DAS + 2 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	274.93	280.10	277.52	43.67	44.09	43.88	291.29	289.00	290.15
T_3 : 40 kg N as basal + 30 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	268.41	272.21	270.31	40.33	42.27	41.30	283.81	283.96	283.88
T_4 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	262.39	267.78	265.09	36.86	39.62	38.24	277.59	279.21	278.40
T_5 : 40 kg N as basal + 20 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	260.85	266.15	263.50	35.62	38.18	36.90	271.31	274.33	272.82
T_6 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	257.58	262.33	259.96	34.38	37.50	35.94	269.07	272.25	270.66
T_7 : 40 kg N as basal + 10 kg N through Urea at 25-30 DAS + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	250.74	261.53	256.14	32.54	36.22	34.38	263.59	270.79	267.19
T_8 : 40 kg N as basal + 4 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	248.55	254.48	251.51	30.88	36.20	33.54	259.83	267.11	263.47
T_9 : 40 kg N as basal + 3 foliar sprays of Nano Urea 0.4% when LCC ≤ 4	241.31	249.99	245.65	29.37	34.68	32.03	256.79	264.31	260.55
T_{10} : Control (without N application)	227.34	232.64	229.99	26.50	32.66	29.58	243.747	253.83	248.79
SEm±	10.06	11.91	7.80	3.43	5.24	3.13	10.43	14.03	8.74
C.D. at 5%	29.89	35.39	22.38	NS	NS	NS	NS	NS	NS
C.V. %	6.74	7.78	7.29	17.00	23.73	20.96	6.69	8.88	7.88
Y × T									
SEm±	12.25			4.43			12.36		
C.D. at 5%	NS			NS			NS		

Nano fertilizers are characterized by their very small particle size and large surface area, which are smaller than the pore spaces of plant roots and leaves. This enables them to easily enter plant tissues through the surfaces where they are applied, resulting in better absorption and higher nutrient use efficiency. The smaller particle size also increases the number of particles and their surface area per unit volume, allowing LCC-based nano urea to have more points of contact with plant surfaces. Consequently, this improved interaction enhances nutrient movement into the plant and leads to greater nutrient uptake and utilization. These results were supported the findings of Tarafder et al*.* (2019), Maurya et al*.* (2022), Sharma et al*.* (2022), Sahu et al*.* (2022b) and Parve et al*.* (2023).

3.4 Available Nutrient Status in Soil

The data presented in Table 6 showed that the treatment involving the application of 40 kg N as a basal dose, followed by 40 kg N through urea at 25–30 DAS and another 40 kg N through urea at 40–45 DAS (T_1), resulted in the highest available nitrogen in the soil after the harvest of pearl millet, with a value of 299.34 kg/ha. This treatment was found to be statistically at par with T_2, which received 40 kg N as basal, 40 kg N through urea at 25–30 DAS, and 2 foliar sprays of nano urea (0.4%) when the LCC reading was ≤ 4. While, in case available phosphorus and available potassium status in soil after harvest remained unaffected by various treatments.

An increase in the available nitrogen content of the soil after harvest was recorded in the treatment that received the recommended fertilizer dose. This could be attributed to the higher quantity of fertilizer applied, which provided a sufficient and timely supply of nutrients to fulfill the crop’s requirements during its growth period. The results are in accordance with the findings of Barad et al*.* (2018), Sahu et al. (2022a) and Soundarya et al*.* (2024).

4. CONCLUSION

From the findings of the two-year field experiment, it can be concluded that applying 40 kg N as a basal dose, followed by another 40 kg N through urea at 25–30 days after sowing, together with 2 foliar sprays of 0.4% nano urea when the LCC value is ≤ 4, proved most effective in pearl millet. This treatment significantly improved the protein content, and the nitrogen and phosphorus concentration in both grain and fodder. It also enhanced the uptake of nitrogen, phosphorus, and potassium by the crop and increased the amount of available nitrogen remaining in the soil after harvest.

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 this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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