International Journal of Research in Agronomy 2025; 8(9): 250-256

E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(9): 250-256
Received: 19-06-2025
Accepted: 21-07-2025

R Joseph Koireng
All India Coordinated Research Project on Forage Crops and Utilization, Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal, Manipur, India

Ramasubramanian Sabarivasan
Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal, Manipur, India

Kholu Mary
Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal, Manipur, India

Corresponding Author:
R Joseph Koireng
All India Coordinated Research Project on Forage Crops and Utilization, Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal, Manipur, India

Sustainable nitrogen management in fodder oats: Performance of foliar nano-urea on yield, quality and soil health optimization

R Joseph Koireng, Ramasubramanian Sabarivasan and Kholu Mary

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i9d.3757

Abstract
Efficient nitrogen management in fodder oats is critical for optimizing productivity and forage quality while minimizing environmental losses. Nano-urea offers potential to enhance nitrogen-use efficiency under reduced basal nitrogen (N) regimes. A two-year field study (2022-23, 2023-24) at Central Agricultural University, Imphal, India, evaluated ten N management strategies combining basal N levels (0-100% RDN) with foliar sprays of nano-urea and conventional urea in single-cut fodder oats (*Avena sativa* L.). Foliar nano-urea @ 6 ml $L^{-1}$with 75% RDN (T_7) produced the highest green fodder (379.5 q ha^{-1}) and dry matter yield (82.6 q ha^{-1}), exceeding full conventional N (100% RDN) by 2.8% and 1.5%, respectively. Crude protein yield (8.99 q ha^{-1}) and economic returns (B:C = 2.09) were also maximized in T_7. Soil residual N (261 kg ha^{-1}) and P-K levels were significantly higher under nano-urea treatments compared with conventional fertilization. Principal component analysis revealed T_7 and T_2 as the most productive and profitable treatments, explaining 72.6% of total trait variability. Foliar nano-urea allows a 25% reduction in soil-applied N without compromising yield, forage quality, or profitability while improving soil nutrient status. Nano-urea thus represents a sustainable and cost-effective N management strategy for fodder oat production systems.

Keywords: Fodder oats, forage yield, nano-urea, nitrogen management

1. Introduction

Oat (*Avena sativa* L.) is one of the most common cereals that are grown on approximately 10 million hectares across the globe (Leszczynska *et al*., 2023) [11]. Most oat production is fed to livestock, unlike other cereals: approximately 74% of world oat production is fed to livestock as either green forage or animal straw (Chand *et al*., 2025) [2]. Oat forage is valued for its nutritional balance; fresh oat herbage contains roughly 10-11% crude protein and abundant fiber (Das *et al*., 2015) [4], and it produces high biomass yields even on marginal lands (Tobiasz-Salach *et al*., 2023) [21].

Like other cereals, nitrogen (N) has a strong stimulatory effect on vegetative growth, which includes increasing leaf area, stem elongation, and tillering (Shekara *et al*., 2024) [19]. Nitrogen also improves forage quality so higher N availability raises the crude protein content of oat forage (Liu *et al*., 2025) [12]. In fodder oats, N fertilization frequently yields large increases in both green and dry matter yields and in forage protein (Goyal *et al*., 2025) [9], underlining N's pivotal role in supporting both yield and nutritive quality of oat forage.

Nevertheless, the conventional urea-based N management in cereals is associated with low efficiency (Tripathi *et al*., 2025) [22]. Field crops generally utilize less than half of the fertilizer N applied, and the rest is lost to the environment. In practical farming, urea's agronomic efficiency often lies in the 20-50% range; much N is never captured by the plant (Govindasamy *et al*., 2023). [8] These inefficiencies mean that farmers must apply large N rates to sustain oats yields, but this comes with consequences: environmental losses of N (as nitrate pollution and nitrous oxide emissions) rise steeply with excess N inputs (Zhao *et al*., 2022) [24]. The conventional urea manure fails to use N efficiently and leads to unsustainable losses (Mahmud *et al*., 2021) [13]. Optimizing N management in oats is not only about boosting forage yields and feed protein, but also about protecting soil health, water quality and climate. Sustainable production of oats demands the production of grains and forage to reach the maximum output per unit N with minimal leaching of nitrates and loss of gases (Singh *et al*., 2024) [20]. Nano-urea has emerged as a novel tool to address these challenges.

Nano-urea is a nano-engineered nitrogen fertilizer in which urea is converted into nanoparticles (~1-100 nm) suspended in liquid (De and Das, 2024) [6]. By design, nano-urea contains a much lower N concentration (around 4% N by weight) and ultra-small particle size (Kumar *et al*., 2023) [10]. These characteristics provide nano-urea with special benefits: the nano-meter-size droplets can dissolve rapidly on the leaf or soil surfaces (Abhiram, 2023) [1] and release N at a slower and more even rate (Verma *et al*., 2023) [23]. Studies observe that these nano-formulations provide controlled N release, high leaf uptake, and less N losses compared to conventional urea application (Mim *et al*., 2025) [14]. Nano-urea can therefore be used as a foliar to overcome the constraints of soil N fertilizer because it diffuses through the stomata and cuticle and is not subject to soil fixation and microbial immobilization (Saurabh *et al*., 2024) [18]. Hence, this study explores how nano-urea foliar application impacts fodder oat growth, forage quality, and soil N dynamics, which is also a timely and critical endeavor for advancing sustainable livestock forage systems.

2. Materials and Methods

A field experiment was conducted at AICRP on Forage Crops, Central Agricultural University, Imphal, Manipur, India, during the rabi seasons of 2022-23 and 2023-24. It was laid out in a Randomized Block Design (RBD) with ten treatments (T_1-T_{10}) and three replications. The experimental crop was single-cut fodder oat (*Avena sativa* L., var. RO-11-1). Each plot measured 4.0 x 4.0 m with 25 cm row-to-row spacing. The recommended fertilizer dose of 100:40:30 kg N:P_2O_5:K_2O ha^{-1} was adopted, with nitrogen applied in three splits (50% basal, 25% at 25 DAS, and 25% at 45 DAS), while phosphorus and potassium were applied basally. Treatments consisted of different nitrogen management strategies, including control (T_1: no nitrogen), full recommended dose of nitrogen (T_2: 100% RDN), Nano-urea sprays at varying concentrations combined with 50-75% RDN (T_3-T_8), and conventional urea sprays (T_9-T_{10}). Foliar applications of Nano-urea or urea were imposed at 25 and 45 DAS using 500 L spray solution ha^{-1}. Essentially, experimental error was minimized by randomization of treatments in every replication to provide a strong statistical comparison of treatment efficacies on fodder productivity, nutritive quality, and soil nutrient dynamics.

3. Results and Discussion

3.1 Effect on Growth and Morphological Traits

Application of various nano-urea combinations recorded a significant variation in plant height and leaf:stem ratio (Table 1). The tallest plants (144.27 cm) were recorded in the treatment 50% RDN + 2% urea spray (T_{10}), followed by the treatment 100% recommended dose of nitrogen (T_2) witha plant height of 142.06 cm, whereas the control without nitrogen (T_1) produced the shortest plants (120.83 cm). Treatments involving Nano-urea addition with reduced soil-applied nitrogen showed intermediate heights, ranging from 128.34 cm in the treatment utilized 75% RDN + Nano-urea @ 2 ml L^{-1}(T_3) to 138.66 cm in 50% RDN + Nano-urea @ 6 ml L^{-1}(T_8). T_2 and T_{10} treatments encouraged vegetative elongation, whereas Nano-urea treatment maintained sufficient growth with no excessive stem elongation, possibly leading to effective biomass partitioning and increased fodder productivity.

The leaf:stem ratio (LSR), which is one of the primary determinants of forage quality, varied between treatments (0.21 to 0.27). The highest LSR values (0.27 and 0.26) were recorded in the treatments T_9 and T_{10}, respectively. Nano-urea integrated treatments (T_3-T_8) maintained moderate LSR values (0.21-0.24), reflecting a balanced canopy structure conducive to both productivity and nutritive quality.

Corresponding growth of plant height and leaf area was observed in fodder oat and wheat experiments in which spraying of nano-urea (nano-fertilizer) in combination with partial replacement of conventional N showed enhanced N availability and more efficient canopy formation during nano-N regimes (Rawate *et al*., 2022; Fayaz, 2023) [16, 7].

Table 1: Effect of Nano-urea and conventional nitrogen management on plant height and leaf: stem ratio of single-cut fodder oat

Treatments	Plant height (cm)			Leaf stem ratio		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	111.32	130.33	120.83	0.25	0.25	0.25
T_2	135.23	148.89	142.06	0.2	0.28	0.24
T_3	121.58	135.11	128.34	0.17	0.25	0.21
T_4	122.7	150.56	136.63	0.17	0.3	0.23
T_5	123.8	137.67	130.73	0.19	0.28	0.24
T_6	131.47	146.78	139.12	0.19	0.27	0.23
T_7	143.72	133	138.36	0.13	0.29	0.21
T_8	131.43	145.89	138.66	0.18	0.25	0.22
T_9	131.83	135.56	133.69	0.23	0.31	0.27
T_{10}	148.2	140.33	144.27	0.22	0.3	0.26
S.Em$\pm$	3.18	2.65	2.05	0.01	0.01	0.01
CD at 5%	9.46	7.88	6.09	0.04	0.02	0.02
CV (%)	4.24	3.27	2.63	10.7	5.05	5.27

T_1 - Control (no nitrogen); T_2 - 100 kg N ha^{-1} (RDN); T_3 - 75% RDN + Nano-urea @ 2 ml L^{-1}; T_4 - 50% RDN + Nano-urea @ 2 ml L^{-1}; T_5 - 75% RDN + Nano-urea @ 4 ml L^{-1}; T_6 - 50% RDN + Nano-urea @ 4 ml L^{-1}; T_7 - 75% RDN + Nano-urea @ 6 ml L^{-1}; T_8 - 50% RDN + Nano-urea @ 6 ml L^{-1}; T_9 - 75% RDN + 2% urea spray; T_{10} - 50% RDN + 2% urea spray; RDN - recommended dose of nitrogen; S.Em$\pm$ standard error of mean; CD - critical difference at 5% level; CV - coefficient of variation.

3.2 Effect on Fodder Productivity

Nano-urea under reduced conventional nitrogen regimes recorded significant differences among treatments for both green fodder and dry matter yields (Table 2). The highest green fodder yield (379.52 q ha^{-1}) and dry matter yield (82.62 q ha^{-1}) were recorded in the treatment that utilized 75% RDN + Nano-urea @ 6 ml L^{-1}(T_7), which was statistically superior to the conventional nitrogen application in treatment T_2in which 100% recommended dose of nitrogen is applied (369.12 and 81.41 q ha^{-1}, respectively). The next best performance was observed in the treatment T_5: 75% RDN + Nano-urea @ 4 ml L^{-1}(360.40 and 79.49 q ha^{-1}, respectively). In contrast, the control (T_1) produced the lowest yields (213.65 and 52.51 q ha^{-1}).

Treatments with reduced nitrogen levels supplemented with Nano-urea (T_3, T_4, T_6, T_8) outperformed the control but were inferior to T_2 and T_7, indicating that foliar Nano-urea could partially compensate for reduced soil-applied nitrogen. Remarkably, T_9: 75% RDN + 2% urea spray also showed relatively high dry matter yield (75.90 q ha^{-1}), but it remained lower than Nano-urea-based treatments such as T_7 and T_5. The statistical data demonstrated that Nano-urea integration, especially T_7, is better than conventional fertilization. These results indicate that Nano-urea not only increases biomass generation but also enables a reduction of soil-applied nitrogen by 25% without yield loss. This has been attributed to an increase in foliar uptake and efficiency of use of Nano-urea, which aids in sustained levels of nitrogen during crucial growth phases. Similar results were recorded by Chethan Babu *et al*. (2025) [3], that field trials on oats and other cereals have recorded higher green fodder and dry matter yields with integrated nano-urea sprays.

Table 2: Effect of Nano-urea and conventional nitrogen management on green fodder yield and dry matter yield of single-cut fodder oat

Treatments	Green Fodder yield (q ha^{-1})			Dry Matter Yield (q ha^{-1})		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	208.67	218.63	213.65	51.64	53.38	52.51
T_2	360.8	377.44	369.12	76.82	86	81.41
T_3	321	287.86	304.43	66.34	64.92	65.63
T_4	291.67	245.13	268.4	57.48	56.14	56.81
T_5	351.73	369.06	360.4	75.14	83.85	79.49
T_6	308.33	255.21	281.77	58.7	54.43	56.57
T_7	372.2	386.84	379.52	78.31	86.92	82.62
T_8	312	257.61	284.8	63.3	62.47	62.89
T_9	338.17	314.53	326.35	80.29	71.51	75.9
T_{10}	313.9	281.03	297.46	76.9	57.25	67.07
S.Em±	16.76	21.73	13.57	3.4	5.4	3.13
CD at 5%	49.79	64.55	40.33	10.12	16.03	9.3
CV (%)	9.13	12.57	7.62	8.61	13.81	7.96

T_1 - Control (no nitrogen); T_2 - 100 kg N ha^{-1} (RDN); T_3 - 75% RDN + Nano-urea @ 2 ml L^{-1}; T_4 - 50% RDN + Nano-urea @ 2 ml L^{-1}; T_5 - 75% RDN + Nano-urea @ 4 ml L^{-1}; T_6 - 50% RDN + Nano-urea @ 4 ml L^{-1}; T_7 - 75% RDN + Nano-urea @ 6 ml L^{-1}; T_8 - 50% RDN + Nano-urea @ 6 ml L^{-1}; T_9 - 75% RDN + 2% urea spray; T_{10} - 50% RDN + 2% urea spray; RDN - recommended dose of nitrogen; S.Em± standard error of mean; CD - critical difference at 5% level; CV - coefficient of variation.

3.3 Effect on Forage Quality

Significant variation was observed in crude protein (CP) yield and concentration among treatments. The maximum CP yield (8.99 q ha^{-1}) was recorded in the treatment that utilized 75% RDN + Nano-urea @ 6 ml L^{-1} (T_7), which was statistically superior to all other treatments. This was followed by (8.36 q ha^{-1}) the treatment that used 75% RDN + Nano-urea @ 4 ml L^{-1} (T_5) and 100% recommended dose of nitrogen (T_2) (8.16 q ha^{-1}). In contrast, the control (T_1) recorded the lowest CP yield (4.80 q ha^{-1}).

Table 3: Effect of Nano-urea and conventional nitrogen management crude protein yield of single-cut fodder oat

Treatment	Crude protein yield (q ha^{-1})		
	2022-23	2023-24	Pooled
T_1	4.76	4.83	4.8
T_2	7.73	8.58	8.16
T_3	6.37	6.87	6.62
T_4	5.78	6.17	5.98
T_5	7.96	8.76	8.36
T_6	5.91	5.17	5.54
T_7	8.77	9.2	8.99
T_8	6.24	7.06	6.65
T_9	8.1	7.18	7.64
T_{10}	6.37	5.88	6.12
S.Em±	0.33	0.54	0.31
CD at 5%	0.97	1.59	0.92
CV (%)	8.34	13.33	7.78

T_1 - Control (no nitrogen); T_2 - 100 kg N ha^{-1} (RDN); T_3 - 75% RDN + Nano-urea @ 2 ml L^{-1}; T_4 - 50% RDN + Nano-urea @ 2 ml L^{-1}; T_5 - 75% RDN + Nano-urea @ 4 ml L^{-1}; T_6 - 50% RDN + Nano-urea @ 4 ml L^{-1}; T_7 - 75% RDN + Nano-urea @ 6 ml L^{-1}; T_8 - 50% RDN + Nano-urea @ 6 ml L^{-1}; T_9 - 75% RDN + 2% urea spray; T_{10} - 50% RDN + 2% urea spray; RDN - recommended dose of nitrogen; S.Em± standard error of mean; CD - critical difference at 5% level; CV - coefficient of variation.

Crude protein concentration followed a similar trend. The highest pooled CP percentage was observed in T_7 (10.90%), followed by T_5 (10.53%) and T_8: 50% RDN + Nano-urea @ 6 ml L^{-1} (10.58%), whereas the control (T_1) registered the lowest CP concentration (9.13%). Treatments with reduced nitrogen levels combined with Nano-urea sprays (T_3, T_4, T_6, T_8) maintained CP concentrations between 9.60% and 10.58%, indicating their ability to sustain forage nutritive quality even under reduced basal nitrogen.

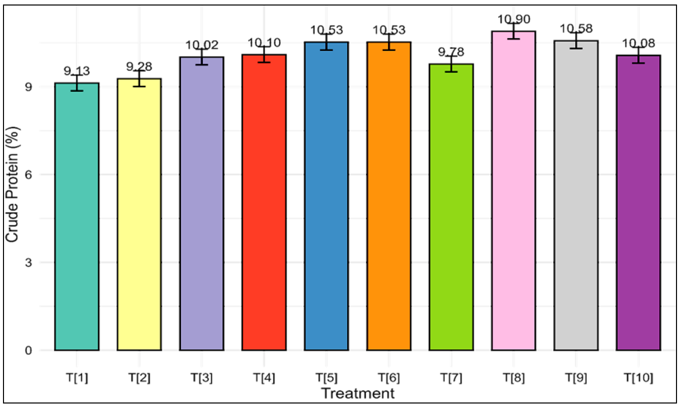

Fig 1: Effect of Nano-urea and conventional nitrogen management on crude protein%

Nano-urea-integrated treatments have been shown to enhance crude protein as they enhance nitrogen absorption and translocation via the foliar pathway to improve amino acid and protein synthesis in plant tissues. Interestingly, the treatment T_7 performed better than the complete application of nitrogen (T_2), which shows that Nano-urea can match the supply of nitrogen to crop demand, thus improving crop yield and quality. This increase in CP content and yield directly affects livestock diet, as increased protein content of forage increases livestock feed efficiency and performance. Similar gains in grain/straw protein or forage CP have been documented where nano-N (or nano-DAP in combination) was used to complement reduced basal N (Reddy *et al*., 2025) [17].

3.4 Effect of Nano-Urea on the Economic Analysis of Single-Cut Fodder Oat

Economic returns varied significantly due to the application of nano-urea on single-cut fodder oat among the treatments (Table4). The highest gross return (₹75,904 ha^{-1}), net return (₹39,653 ha^{-1}), and benefit-cost (B:C) ratio (2.09) were achieved in the treatment utilized 75% RDN + Nano-urea @ 6 ml L^{-1} (T_7), which was statistically at par with the treatment utilized 100% recommended dose of nitrogen (T_2) (gross return ₹73,824 ha^{-1}, net return ₹38,376 ha^{-1}, B:C ratio 2.08). This denotes that Nano-urea application with low nitrogen loadings could achieve the same or even exceed the economic advantages of conventional soil-applied nitrogen.

Other Nano-urea treatments also demonstrated strong economic performance. The treatment with 75% RDN + Nano-urea @ 4 ml L^{-1} (T_5) recorded pooled net returns of ₹36,279 ha^{-1} with a B:C ratio of 2.01, closely comparable to T_2 and T_7. In contrast, the control(T_1) registered the lowest profitability (gross return ₹42,730 ha^{-1}, net return ₹17,650 ha^{-1}, B:C ratio 1.70), reflecting the critical importance of nitrogen fertilization in fodder oat production. Among the conventional foliar urea sprays, T_9: 75% RDN + 2% urea spray (net return ₹29,953 ha^{-1}, B:C ratio 1.85) performed better than T_{10}: 50% RDN + 2% urea spray (net return ₹24,723 ha^{-1}, B:C ratio 1.71), but both were inferior to their Nano-urea counterparts (T_5 and T_7). This also underscores the cost-effectiveness and increased return efficiency of Nano-urea as compared to conventional urea sprays.

The statistical analysis confirmed significant treatment differences in profitability. The superior economic efficiency of T_7 demonstrates that Nano-urea supplementation can reduce the cost of nitrogen input by 25% and yet still achieve or enhance returns, providing a viable and economical nutrient management strategy that can be used to grow fodder oats. This corroborates the results of Dash *et al*. (2025) [5], who found that nano-urea integration increases agronomic N efficiency and profitability by reducing fertilizer input costs while maintaining or raising yields

Table 4: Effect of Nano-urea and conventional nitrogen management on gross return, net return, and benefit-cost ratio of single-cut fodder oat

Treatments	Gross return (₹ha^{-1})			Net return (₹ ha^{-1})			B: C ratio		
	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled	2022-23	2023-24	Pooled
T_1	41733	43726	42730	16653	18646	17650	1.66	1.74	1.7
T_2	72160	75487	73824	36713	40040	38376	2.04	2.13	2.08
T_3	64200	57573	60886	28849	22222	25536	1.82	1.63	1.72
T_4	58333	49026	53679	23530	14222	18876	1.68	1.41	1.54
T_5	70347	73812	72079	34546	38011	36279	1.96	2.06	2.01
T_6	61667	51043	56355	26413	15789	21101	1.75	1.45	1.6
T_7	74440	77368	75904	38189	41117	39653	2.05	2.13	2.09
T_8	62400	51521	56961	26696	15818	21257	1.75	1.44	1.6
T_9	67633	62906	65270	32317	27589	29953	1.92	1.78	1.85
T_{10}	62780	56205	59493	28010	21435	24723	1.81	1.62	1.71
S.Em±	3352	4345	2715	3352	4345	2715	0.1	0.13	0.08
CD at 5%	9958	12910	8066	9958	12910	8066	0.29	0.38	0.23
CV (%)	9	13	8	20	30	17	9.23	12.71	7.49

T_1 - Control (no nitrogen); T_2 - 100 kg N ha^{-1} (RDN); T_3 - 75% RDN + Nano-urea @ 2 ml L^{-1}; T_4 - 50% RDN + Nano-urea @ 2 ml L^{-1}; T_5 - 75% RDN + Nano-urea @ 4 ml L^{-1}; T_6 - 50% RDN + Nano-urea @ 4 ml L^{-1}; T_7 - 75% RDN + Nano-urea @ 6 ml L^{-1}; T_8 - 50% RDN + Nano-urea @ 6 ml L^{-1}; T_9 - 75% RDN + 2% urea spray; T_{10} - 50% RDN + 2% urea spray; RDN - recommended dose of nitrogen; S.Em± standard error of mean; CD - critical difference at 5% level; CV - coefficient of variation.

3.5 Soil Nutrient Dynamics

The level of available soil nutrients following oat harvest with varied nitrogen management practices differed considerably (Table 5). Treatments did not have significant effects on soil organic carbon and pH, which suggests that short-term use of nano urea did not change these parameters significantly. Conversely, there were significant variations in the available macronutrients, especially nitrogen, between the treatments.

The maximum residual available N (268 and 261 kg ha^{-1}) was recorded in the treatment used 50% RDN + nano @ 4 ml L^{-1}(T_6) and 75% RDN + nano @ 4 ml L^{-1}(T_5) respectively, which were significantly superior to the control (T_1: 231 kg ha^{-1}) and the full conventional RDN treatment (T_2) recorded 238 kg ha^{-1}. Similar trends were observed for available P and K, with nano urea-based treatments (T_5-T_8) consistently maintaining higher levels than conventional fertilization. Among these, treatment with 50% RDN + nano @ 6 ml L^{-1}(T_8) recorded the highest P (13.3 kg ha^{-1}) and K (152 kg ha^{-1}). These results indicate that foliar nano urea application, when combined with low basal nitrogen, enhances nutrient use efficiency and reduces losses, hence maintaining elevated residual nutrient pools in soil.

The increased nutrient availability in soils when using nano urea indicates that a significant percentage of nutrients utilized is still available to further crop cycles, thus helping to preserve soil fertility. This is especially critical in systems based on fodder, where mineral removal is high at any given time and traditional fertilization tends to cause nutrient mining. Several investigations reported similar higher residual N pools or improved post-harvest available N where nano-N was used with reduced basal N (Nandhakumar *et al*., 2025) [15].

Table 5: Effect of Nano-urea and conventional nitrogen management on soil organic carbon, pH, and available nutrients (N, P, K) in single-cut fodder oat fields

Treatments	Soil properties				Available nutrient (kgha^{-1})					
	OC (%)		pH		N		P		K	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
T_1	0.95	0.94	5.18	5.18	232.8	230.8	10.7	10.2	131.8	130.3
T_2	0.97	0.97	5.22	5.23	239.2	236.9	11.2	11.1	139.2	136.8
T_3	0.99	1.01	5.19	5.18	251.2	250.8	12.8	12.7	148.5	139.1
T_4	0.98	1	5.15	5.16	250.5	259.3	12.3	11.9	146.2	143.7
T_5	1.01	1.02	5.26	5.25	260.3	261.6	12.7	11.8	153.7	151.6
T_6	0.93	0.94	5.24	5.24	269.1	267.3	13.2	12.2	154.6	151.8
T_7	0.94	0.96	5.2	5.21	253.4	251.6	13.8	12.7	154.9	152.4
T_8	1.02	1.03	5.23	5.23	256.9	253.1	13.9	12.8	152.7	151.3
T_9	0.93	0.93	5.24	5.22	259.8	259.2	12.6	11.9	149.2	146.7
T_{10}	1.01	1.01	5.19	5.17	236.3	235.8	11.8	11.3	143.8	141.8
Initial	1.02	1.01	5.22	5.24	263.7	260.3	14.2	13.9	160.6	158.2

T_1 - Control (no nitrogen); T_2 - 100 kg N ha^{-1} (RDN); T_3 - 75% RDN + Nano-urea @ 2 ml L^{-1}; T_4 - 50% RDN + Nano-urea @ 2 ml L^{-1}; T_5 - 75% RDN + Nano-urea @ 4 ml L^{-1}; T_6 - 50% RDN + Nano-urea @ 4 ml L^{-1}; T_7 - 75% RDN + Nano-urea @ 6 ml L^{-1}; T_8 - 50% RDN + Nano-urea @ 6 ml L^{-1}; T_9 - 75% RDN + 2% urea spray; T_{10} - 50% RDN + 2% urea spray; RDN - recommended dose of nitrogen; S.Em± standard error of mean; CD - critical difference at 5% level; CV - coefficient of variation.

3.6 Correlation Analysis

Correlation analysis among growth, yield, and quality traits of fodder oat (Fig. 2) revealed a strong positive correlation among green fodder yield, dry matter yield, and crude protein yield ($r = 0.95$ to 0.98), indicating that enhancing any of these traits would simultaneously improve the others. Crude protein% recorded only moderate correlations with yield-related traits ($r = 0.61$ to 0.72), while plant height exhibited a moderate positive association with productivity parameters ($r \approx 0.63$ to 0.67). In contrast, the leaf-to-stem ratio was negatively correlated with yield and crude protein yield ($r = -0.40$ to -0.43), suggesting a trade-off between higher leafiness and total biomass accumulation. These findings demonstrate that although the main fodder productivity factors are strongly interconnected, crude protein concentration and leaf stem ratio have an independent effect on each other, emphasizing the need to balance yield and nutritive quality in breeding and management strategies.

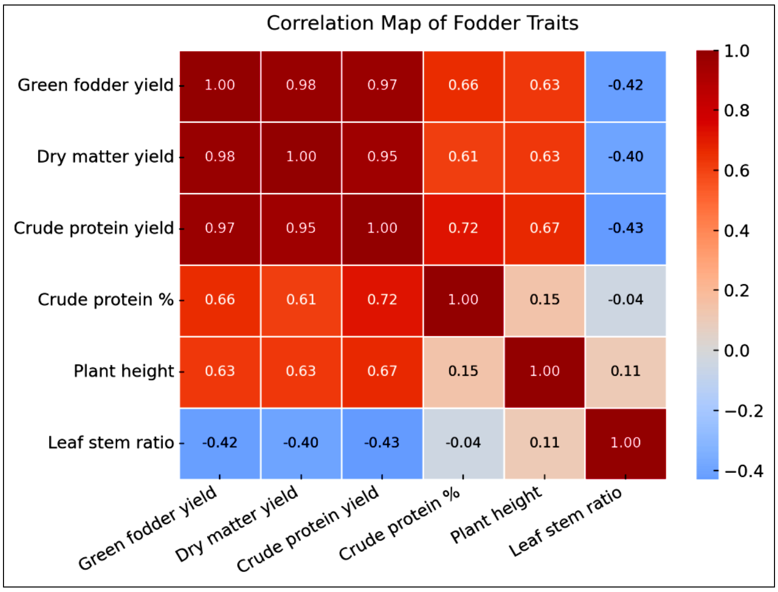

Fig 2: Correlation Matrix between Single-cut Fodder traits

3.7 Regression Analysis

Regression analysis of pooled data demonstrated that green fodder yield was strongly predicted by dry matter yield and plant height, whereas the effect of leaf stem ratio was negligible. The fitted regression model (Fig. 3) explained 95.3% of the total variation in fodder yield ($R^2 = 0.953$; Adjusted $R^2 = 0.929$). Among the predictors, dry matter yield had the most significant effect ($\beta = 4.08$, $p < 0.001$), indicating that for every 1 q ha^{-1} increase in dry matter yield, green fodder yield increased by approximately 4.08 q ha^{-1}. Plant height also exhibited a significant positive influence ($\beta = 1.81$, $p = 0.034$), contributing 1.81 q ha^{-1} to a green fodder yield cm^{-1} increase in plant height. In contrast, leaf stem ratio was non-significant ($p = 0.702$), suggesting limited predictive value. The model's stability was confirmed by variance inflation factor (VIF) values (<2 for all predictors), indicating the absence of multicollinearity. Overall, the results confirm that dry matter yield is the strongest determinant of fodder productivity, followed by plant height.

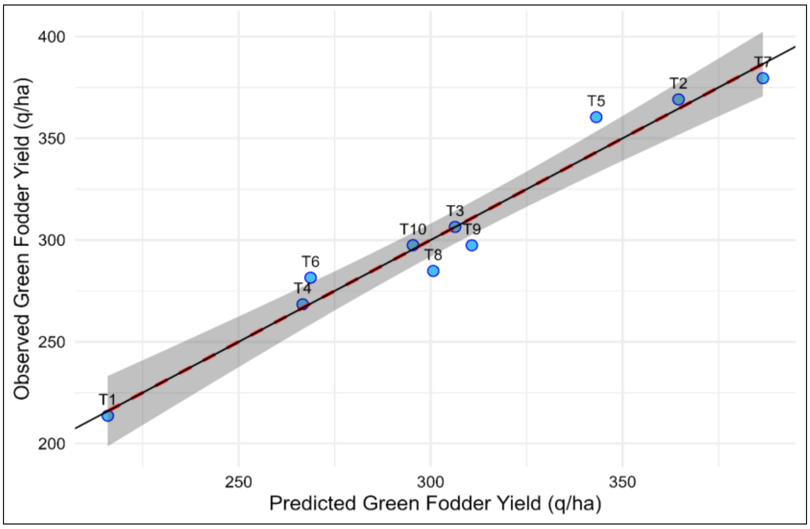

Fig 3: Observed Vs Predicted Green Fodder

3.8 Principal Component Analysis for Treatment Comparison

Eigenvalue analysis (Table 6) revealed that the two largest principal components (PC1 and PC2) accounted for 72.56% of the total variance, providing a reliable two-dimensional representation of the dataset.

Table 6: Eigenvalues, percentage variance, and cumulative variance explained by principal components derived from growth, yield, quality, economic, and soil fertility traits of fodder oat

Principal Component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	7.06	50.45	50.45
PC2	3.1	22.11	72.56
PC3	1.34	9.56	82.13
PC4	1.04	7.39	89.52
PC5	0.66	4.73	94.25
PC6	0.44	3.13	97.38
PC7	0.19	1.34	98.72
PC8	0.12	0.87	99.58
PC9	0.06	0.42	100

Principal Component Analysis (PCA) of growth, yield, quality, and economic traits in fodder oat discovered that the first two principal components (PC1 and PC2) explained 72.56% of the total variance, indicating effective dimensionality reduction. The biplot (Fig. 4) exhibited strong discrimination of treatments, utilized 75% RDN + Nano-urea @ 6 ml L^{-1}(T_7) and 100% RDN (T_2) located positively along PC1, closely associated with green fodder yield, dry matter yield, crude protein yield, gross return, and net return, suggesting their superiority in overall productivity and profitability. Treatments with 75% RDN + Nano-urea @ 4 ml L^{-1} (T_5) and 75% RDN + 2% urea spray (T_9) were also grouped near this group, reflecting strong yield-quality associations. In contrast, contrast (T_1) and treatment with 50% RDN + Nano-urea @ 2 ml L^{-1}(T_4) were located on the negative side of PC1, indicating less superior performance across productivity traits. PC2 was primarily influenced by crude protein percentage and soil parameters (OC and pH), with treatments such as (T_8) showing closer alignment to quality traits rather than yield attributes. This pattern suggests that nano-urea supplementation at 75% RDN enhances both yield and economic returns, while lower nitrogen levels are insufficient to sustain high productivity.

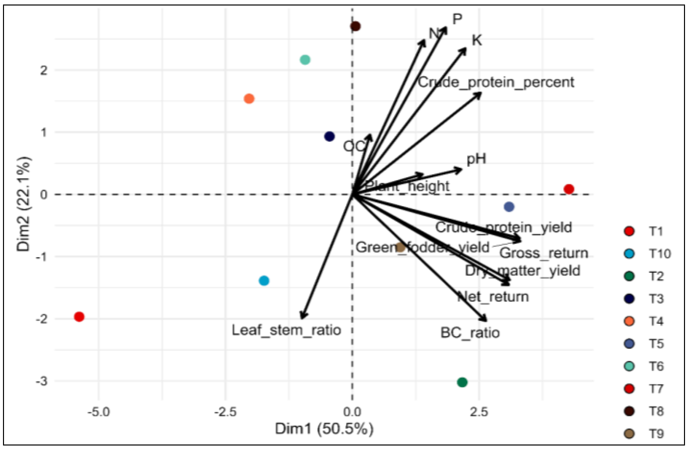

Fig 4: PCA for treatment comparisons

4. Conclusion

This two-year research indicates that a combination of foliar application of nano-urea with a lower basal application of N enhances fodder oat productivity, crude protein yield, and economic returns significantly without compromising soil fertility. Treatment with 75% RDN + nano-urea (6 ml L^{-1}) was effective than the full recommended N rates, so that a 25% reduction in the use of conventional fertilizers was possible. Increased residual soil N and equal P-K status also underscores the importance of nano-urea in increasing nutrient-use efficiency and maintaining soil health. These results highlight the opportunity of nano-urea to be a climate-sensitive and resource-efficient substitute to intensive fodder production systems.

References

1. Abhiram G. Contributions of Nano-Nitrogen Fertilizers to Sustainable Development Goals: A Comprehensive Review. Nitrogen. 2023;4(4):397-415. doi:10.3390/nitrogen4040028.
2. Chand S, Kumar S, Roy AK, Vijay D, Choudhary BB, Indu, *et al*. Analyzing trends and future projections in fodder oats (*Avena sativa* L.) for quality seed production in India. Front Plant Sci. 2025;16:1525422. doi:10.3389/fpls.2025.1525422.
3. Chethan Babu RT, Singh M, BR, PBR, Kumar R, Kumar B, *et al*. Partial substitution of conventional nitrogen fertilizers with nano urea and plant growth-promoting rhizobacteria in fodder oats. Range Manage Agrofor. 2025;46(01):123-8. doi:10.59515/rma.2025.v46.i1.17.
4. Das LK, Kundu SS, Kumar D, Datt C. Fractionation of carbohydrate and protein content of some forage feeds of ruminants for nutritive evaluation. Vet World. 2015;8(2):197-202. doi:10.14202/vetworld.2015.197-202.
5. Dash PP, Koireng RJ, Shamurailatpam D, Parida SK, Devi NS, Singh NG. Impact of nano fertilizers on growth, yield and economics of fodder oats (*Avena sativa* L.). Int J Res Agron. 2025;8(3):261-4. doi:10.33545/2618060X.2025.v8.i3d.2640.
6. De N, Das T. Nano urea and its superiority over urea as fertilizer elaborating some applications-an overview. Int J Sci Res Sci Technol. 2024;11(4).
7. Fayaz S. Effect of Urea and foliar application of Nano Urea on growth and yield of different varieties of fodder oat (*Avena sativa* L.) under north western Punjab condition. Agric Assoc Text Chem Crit Rev J. 2023;11(2):62-8.
8. Govindasamy P, Muthusamy SK, Bagavathiannan M, Mowrer J, Jagannadham PTK, Maity A, *et al*. Nitrogen use efficiency—A key to enhance crop productivity under a changing climate. Front Plant Sci. 2023;14:1121073. doi:10.3389/fpls.2023.1121073.
9. Goyal A, Chavan SS, Mohite RA, Shaikh IA, Chendake Y, Mohite DD. Emerging trends and perspectives on nano-fertilizers for sustainable agriculture. Discover Nano. 2025;20(1):97. doi:10.1186/s11671-025-04286-8.
10. Kumar A, Ram H, Kumar S, Kumar R, Yadav A, Gairola A, *et al*. A comprehensive review of nano-urea vs. Conventional urea. Int J Plant Soil Sci. 2023;35(23):32-40.
11. Leszczyńska D, Wirkijowska A, Gasiński A, Średnicka-Tober D, Trafiałek J, Kazimierczak R. Oat and Oat Processed Products—Technology, Composition, Nutritional Value, and Health. Appl Sci. 2023;13(20):11267. doi:10.3390/app132011267.

12. Liu W, Yan S, Jiang N, Li M, Yin L, Zhang S, *et al*. Interaction of nitrogen and mowing frequency in enhancing regeneration and crude protein content of forage oat in Northwestern of China. Field Crops Res. 2025;331:109994. doi:10.1016/j.fcr.2025.109994.
13. Mahmud K, Panday D, Mergoum A, Missaoui A. Nitrogen Losses and Potential Mitigation Strategies for a Sustainable Agroecosystem. Sustainability. 2021;13(4):2400. doi:10.3390/su13042400.
14. Mim JJ, Rahman SMM, Khan F, Paul D, Sikder S, Das HP, *et al*. Towards smart agriculture through nano-fertilizer-A review. Mater Today Sustain. 2025;30:101100. doi:10.1016/j.mtsust.2025.101100.
15. Nandhakumar MR, Muthukrishnan R, Nivethadevi P, Kiruthika K, Tamilarasan C. Influence of Nano Urea on Growth Yield and Nutrient Uptake of Blackgram. Legume Research - An International Journal. 2025. doi:10.18805/LR-5384.
16. Rawate D, Kumar A, Patel J, Agrawal A, Agrawal H, Pandey D, *et al*. Effect of nano urea on productivity of wheat (*Triticum aestivum* L.) under irrigated condition. J Pharmacogn Phytochem. 2022. p. 1279-82.
17. Reddy KS, Shivay YS, Kumar D, Parida BK, Bora R, Borate RB, *et al*. Nano DAP augments productivity, phosphorus use efficiency, and profitability of spring wheat. Sci Rep. 2025;15(1):24771. doi:10.1038/s41598-025-92364-3.
18. Saurabh K, Prakash V, Dubey AK, Ghosh S, Kumari A, Sundaram PK, *et al*. Enhancing sustainability in agriculture with nanofertilizers. Discover Appl Sci. 2024;6(11):559. doi:10.1007/s42452-024-06267-5.
19. Shekara B, Chikkarugi N, Rani N. Influence of Nano-Urea on Productivity and Quality of Fodder Oat (*Avena sativa* L.) in Southern Dry Zone of Karnataka. Mysore J Agric Sci. 2024;58(4).
20. Singh P, Tomar M, Singh AK, Yadav VK, Saini RP, Swami SR, *et al*. International Scenario of Oat Production and Its Potential Role in Sustainable Agriculture. In: Oat (*Avena sativa*). CRC Press; 2024.
21. Tobiasz-Salach R, Stadnik B, Bajcar M. Oat as a Potential Source of Energy. Energies. 2023;16(16):6019. doi:10.3390/en16166019.
22. Tripathi SC, Kumar N, Venkatesh K. Nano urea's environmental edge and economic efficacy in boosting wheat grain yield across diverse Indian agro-climates. Sci Rep. 2025;15(1):3598. doi:10.1038/s41598-024-83616-9.
23. Verma KK, Song XP, Degu HD, Guo DJ, Joshi A, Huang HR, *et al*. Recent advances in nitrogen and nano-nitrogen fertilizers for sustainable crop production: A mini-review. Chem Biol Technol Agric. 2023;10(1):111. doi:10.1186/s40538-023-00488-3.
24. Zhao C, Liu G, Chen Y, Jiang Y, Shi Y, Zhao L, *et al*. Excessive Nitrogen Application Leads to Lower Rice Yield and Grain Quality by Inhibiting the Grain Filling of Inferior Grains. Agriculture. 2022;12(7):962. doi:10.3390/agriculture12070962.