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Application of nano-urea improves productivity, quality and economics of fodder maize (*Zea mays* L.) in Manipur, a Northeastern hill region of India

R. Joseph Koireng[1*], Sonam Lhamu[1], Konjengbam Maheshwari[2], Tanu Oinam[1], Govindaraj Kamalam Dinesh[3], Osi Siram[1]

[1]Department of Agronomy, College of Agriculture, Central Agricultural University, Imphal-795004, Manipur, India.
[2]Department of Basic Science and Humanities, College of Agriculture, Central Agricultural University, Imphal – 795004, Manipur, India.
[3]Department of Biochemistry, Physiology, Microbiology and Environmental Science, College of Agriculture, Central Agricultural University, Iroisemba, Imphal, Manipur - 795004, India.

[*]**Correspondence**
R. Joseph Koireng
josephkoireng1980@gmail.com

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Background: Optimising nutrient management strategies is crucial to enhance the growth, yield and nutritional quality of fodder maize, while minimizing environmental impacts and reducing input costs. This study was conducted at the Andro Research Station, CAU Imphal, during the kharif seasons of 2022 and 2023, to evaluate the performance of nano-urea under various nitrogen management regimes.

Methods: The experiment was laid out in Randomized Block Design (RBD) with 10 treatments replicated thrice. Treatments included one recommended dose of fertilizers (RDF), six different nitrogen substitution levels with nano-urea (2-6 mL L^{-1}), two foliar urea sprays (2%), and one control (without nitrogen).

Results: The study revealed that by applying 75% recommended dose of nitrogen (RDN) through urea, along with a foliar spray of nano-urea @ 6 mL $L^{-1,}$ achieved comparable productivity to the 100% RDF. This treatment also gave the highest green fodder yield, dry matter yield, and crude protein, along with maximum net return (₹64,208 ha^{-1}) and B:C ratio (2.57). While the RDF also performed well, nano-urea treatments proved to be more economical and sustainable by reducing chemical nitrogen input by 25% without incurring a yield penalty. Higher levels of organic carbon and available nitrogen in post-harvest soil analysis were found under nano-urea treatments as compared to the control.

Conclusion: It was concluded that the foliar spray of nano-urea @ 6 mL L^{-1}, along with 75% recommended dose of nitrogen (RDN), is a viable option to enhance the productivity, profitability, and nutrient use efficiency in fodder maize under acidic subtropical conditions in Imphal.

Keywords: *fodder maize, nano-urea, crude protein, foliar spray, soil fertility*

Introduction

Fodder maize (*Zea mays* L.) is one of the most important forage crops grown in India, valued for its high biomass yield, palatability, as well as for its vital role in sustaining livestock-based farming systems. Maize is cultivated globally across seasons for both grain and fodder purposes, with a fodder productivity potential of 30-55 t ha^{-1} (Arun Kumar et al., 2024). Due to its ability to produce large quantities of nutritious fodder, as well as its adaptability to diverse climatic conditions, maize is widely preferred. The crop is particularly suitable as fodder due to its rapid growth, succulence, palatability, and excellent nutritional quality. However, efficient nutrient management is required in maize cultivation, as it is a nutrient-exhaustive crop. Supplying of quality fodder is important for improving milk production in cattle, as it provides higher crude protein and essential nutrients to the small intestine, thereby enhancing the nitrogen balance in livestock (Kashyap et al., 2023). Given the rising demand for quality fodder and hence the increasing pressure on land resources, improving productivity while minimizing production costs has become essential. Nitrogen (N) is the most critical nutrient for maize, a highly nitrogen-intensive cereal, as it significantly influences the dry matter accumulation, leaf area expansion, as well as the photosynthetic efficiency (Mahdi et al., 2012; Shah et al., 2021). Despite its importance, the efficiency of conventional urea fertilization remains low, with nitrogen use efficiency (NUE) often limited to 30-40% due to volatilization, leaching, and denitrification losses (Yadav et al., 2023). In this regard, nano-fertilizers, particularly nano-urea, have gained importance as a promising innovation that allows controlled nutrient release, enhanced absorption, and reduced environmental losses (Raliya et al., 2017; ICAR-DFR, 2022).

Nano-urea has been reported to substitute 25-50% of soil-applied nitrogen without reducing yields, thus supporting sustainable production systems (Prasad et al., 2017). Each nano-urea particle is approximately 30 nm in size, which offers nearly 10,000 times greater surface area-to-volume ratio as compared to granular urea. This minimal size and surface property enable efficient absorption through foliar application, ensuring a timely nitrogen supply during critical growth stages. As a result, nano-urea foliar sprays have been found to improve crop productivity and quality compared to conventional urea (Srivani et al., 2023). However, despite the potential of nano-urea, research on its effectiveness in fodder maize, particularly in acidic soils of Northeast India, remains limited. Therefore, the present investigation was undertaken to evaluate the impact of varying concentrations of nano-urea on growth, yield, quality economics, and post-harvest soil fertility of fodder maize in Manipur.

Materials and Methods

A field experiment on "Enhancing Productivity, Quality, and Soil Fertility of Fodder Maize (*Zea mays* L.) through Nano-Urea Application under Subtropical Conditions of Imphal" was carried out during the kharif seasons of 2022 and 2023 at Andro Research Station, CAU Imphal which lies between 23º 50'N and 23º 41′ N latitude and 93º 02'E and 94º 47′E longitude with 790 m above mean sea level in Imphal East district of Manipur. The experimental soil was classified as clay loam in texture, acidic in reaction (pH 5.17 in 2022 and 5.09 in 2023), medium in available nitrogen (291.8 and 288.3 kg ha^{-1} in 2022 and 2023, respectively) and phosphorus (16.2 and 17.2 kg ha^{-1}), and high in organic carbon (1.18% and 1.16%) as well as potassium content (286.2 and 283.7 kg ha^{-1}). The experiment was laid out in a Randomized Block Design (RBD) with 10 treatments and three replications. Each replication consisted of 10 plots randomly allotted to the treatments. The net plot size was 4 × 3 m^2. The recommended dose of fertilizer (N: P: K - 150:60:40 kg ha^{-1}) was applied as per the package of practice. The treatments include Control (RDF without N) (T1), RDF (N: P: K @ 150:60:40 kg ha^{-1}) (T2), 75% Recommended dose of N + nano-urea @ 2 mL L^{-1} (T3), 50% Recommended dose of N + nano-urea @ 2 mL L^{-1} (T4), 75% Recommended dose of N + nano-urea @ 4 mL L^{-1} (T5), 50% Recommended dose of N + nano-urea @ 4 mL L^{-1} (T6), 75% Recommended dose of N + nano-urea @ 6 mL L^{-1} (T7), 50% recommended dose of N + nano-urea @ 6 mL L^{-1} (T8), 75% Recommended dose of N + urea (2% foliar spray) (T9) and 50% Recommended dose of N + urea (2% foliar spray) (T10).

The observations were collected on Plant height, leaf: stem ratio, green fodder yield, dry matter yield, crude protein content and yield, Gross return, net return, B:C ratio, and soil fertility parameters like soil OC (%), pH, soil available N, P, K after harvest. All data recorded for different parameters from both years were pooled and analyzed using the analysis of variance (ANOVA) technique for a randomized complete block design, as described by Gomez & Gomez (1984), to conclude the effect of various treatments on the different parameters studied. Critical differences were tested at 5% level of significance. The data were determined using multivariate statistical analysis conducted in Origin Pro software (version 2021, Origin Lab Corporation, Northampton, MA, USA). Each dataset was standardized to unit variance and its normality tested with the Shapiro-Wilk test prior to analysis (Kaiser, 1958). To identify linear associations between the parameters Pearson correlations were performed at a significance level of $p \leq 0.05$, and the results were presented as a color-coded correlation matrix heatmap (Friendly, 2002). PCA analysis was performed using the covariance matrix approach, where components with eigenvalues greater than 1.0 were considered significant contributors to the variance. It was selected to remain in the analysis (Kaiser, 1960). A biplot was generated to illustrate how the treatment combinations and variable loadings were loaded in the first two principal component dimensions, respectively, as recommended in agricultural data analysis procedures (Jolliffe & Cadima, 2016; Gabriel, 1971).

Results

Growth attributes

The data on the growth attributes, such as plant height and leaf-to-stem ratio in fodder maize, as influenced by varied levels of the recommended dose of nitrogen, along with foliar application of different concentrations of nano-urea and urea, are presented in Table 1. It was found that, T7 (75% recommended dose of N + nano-urea at 6 mL L^{-1}) recorded the highest plant height (300.83 cm), significantly outperforming the other treatments. The leaf-to-stem ratio ranged from 0.49 to 1.44 across all treatments, based on the mean data, and was found to be maximum in T5 (1.44), indicating better fodder quality. However, it was statistically comparable to T7 (75% Recommended dose of N + nano-urea @ 6 mL L^{-1}) and T6 (50% Recommended dose of N + nano-urea at 4 mL L^{-1}).

Table 1. Pooled mean data on the effect of Nano-urea on growth parameters of fodder maize

Treatment	Plant height (cm)			Leaf stem ratio		
	2022	2023	Mean	2022	2023	Mean
T1	283.22	245.78	264.50	0.62	0.55	0.59
T2	276.78	272.00	274.39	0.51	0.53	0.52
T3	296.00	259.00	277.50	1.21	0.60	0.91
T4	274.89	257.56	266.22	0.54	0.53	0.54
T5	296.44	267.22	281.83	2.19	0.68	1.44
T6	276.56	247.89	262.22	1.53	0.64	1.09
T7	321.22	280.44	300.83	2.03	0.65	1.34
T8	272.44	257.67	265.06	0.95	0.56	0.76
T9	289.00	264.89	276.94	0.51	0.50	0.51
T10	270.78	239.44	255.11	0.49	0.48	0.49
SEm+	9.39	6.96	5.86	0.31	0.06	0.17
CD at 5%	27.89	20.69	17.40	0.92	NS	0.50
CV (%)	5.69	4.65	3.72	50.62	18.56	35.42

Yield performance

The green fodder yield of maize increased linearly and significantly for each level of nitrogen. A significantly higher green fodder yield maize of 525.39 q ha^{-1} was recorded with the application of 75% Recommended dose of N + nano-urea @ 6 mL L^{-1} (T7) over other N levels Table 2. However, the green fodder yield recorded in T7 was on par with that in T2. Similarly, the dry matter yield (120.66 q ha^{-1}) was found to be the highest under T7, which was on par with T2.

Table 2. Pooled mean data on the effect of Nano-urea on the yield parameters of forage maize

Treatment	Green fodder yield (q/ha)			Dry matter yield (q/ha)		
	2022	2023	Mean	2022	2023	Mean
T1	393.81	399.82	396.82	88.54	86.06	87.30
T2	500.95	505.96	503.46	120.64	100.97	110.80
T3	451.43	447.19	449.31	114.10	97.74	105.92
T4	430.24	432.46	431.35	92.19	76.31	84.25
T5	477.38	475.09	476.23	116.31	96.13	106.22
T6	429.76	430.88	430.32	94.53	85.35	89.94
T7	520.95	529.82	525.39	127.02	114.29	120.66
T8	438.33	442.11	440.22	105.56	91.04	98.30
T9	474.29	466.67	470.48	101.85	93.41	97.63
T10	395.24	384.21	389.72	94.59	84.19	89.39
SEm+	14.88	24.16	15.02	4.91	6.16	4.44
CD at 5%	44.22	71.78	44.63	14.60	18.31	13.20
CV (%)	5.71	9.27	5.76	8.07	11.53	7.77

Quality parameters

Data in respect of crude protein content and crude protein yield at harvest of fodder maize as influenced by varied levels of recommended dose of nitrogen with different foliar concentrations of nano-urea and urea are presented in Figure 1. The crude protein content was significantly influenced by different levels of N with foliar spray treatments.

The application of a 75% recommended dose of N + Urea @ 2% spray (T9) showed a significantly higher crude protein content (10.75%). The crude protein yield was found to be significantly influenced by different levels of N with foliar spray treatments. The application of 75% Recommended dose of N + nano-urea @ 6 mL L^{-1} (T7) showed significantly higher crude protein yield (11.82 q ha^{-1}) and was found on par with RDF (T2: 11.03 q ha^{-1}).

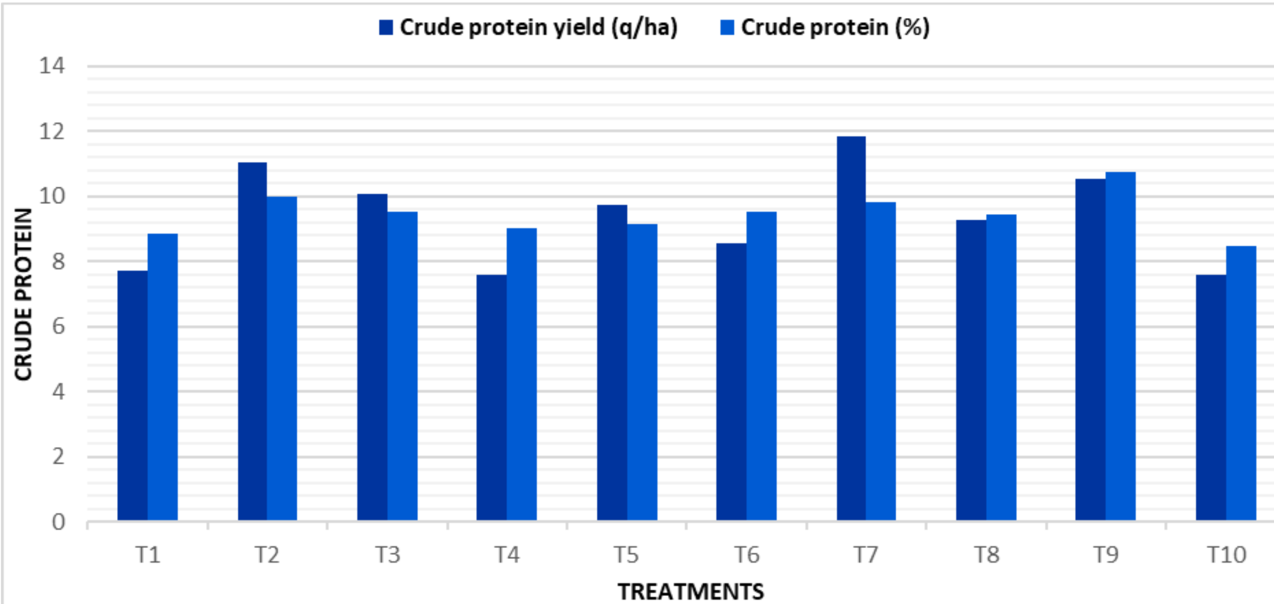

Figure 1. Pooled mean data on the effect of Nano-urea on crude protein content (%) and crude protein yield (q ha^{-1}) of fodder maize at harvest

Economics

Upon pursuing the data (Table 3), economic returns as influenced by urea and nano-urea liquid applications on fodder maize revealed that higher gross and net returns were obtained with a 75% recommended dose of N + nano-urea at 6 mL L^{-1} (T7) (₹1,05,078 ha^{-1} and ₹64,208 ha^{-1}, respectively). The next best alternative was T2 (RDF). The highest benefit–to–cost (B:C) ratio was observed with RDF (T2: 2.61); however, treatments T7 (2.57), T9 (2.46), and T5 (2.38) also recorded comparable values.

Table 3. Pooled mean data on the effect of Nano-urea on the economics of forage maize

Treatment	Gross return (₹/ha)			Net return (₹/ha)			B:C ratio		
	2022	2023	Mean	2022	2023	Mean	2022	2023	Mean
T1	78762	79965	79363	42212	43415	42813	2.15	2.19	2.17
T2	100190	101193	100692	61560	62563	62062	2.59	2.62	2.61
T3	90286	89439	89862	51256	50409	50832	2.31	2.29	2.30
T4	86048	86491	86269	47538	47981	47759	2.23	2.25	2.24
T5	95476	95018	95247	55526	55068	55297	2.39	2.38	2.38
T6	85952	86175	86064	46522	46745	46634	2.18	2.19	2.18
T7	104190	105965	105078	63320	65095	64208	2.55	2.59	2.57
T8	87667	88421	88044	47317	48071	47694	2.17	2.19	2.18
T9	94857	93333	94095	56587	55063	55825	2.48	2.44	2.46
T10	79048	76842	77945	41298	39092	40195	2.09	2.04	2.06
SEm+	2976	4832	3004	2976	4832	3004	0.08	0.13	0.08
CD at 5%	8843	14356	8926	8843	14356	8926	0.23	0.37	0.23
CV (%)	6	9	6	10	16	10	5.74	9.35	5.83

Soil fertility

Post-harvest soil analysis revealed that slightly higher organic carbon and available N were found in nano-urea treatments compared to the control. Among all the treatments, soil pH remained stable (≈5.15), which indicates that no adverse effects were incurred on the soil.

Table 4. Pooled mean data on the effect of Nano-urea on the soil chemical properties and available nutrients of forage maize soil

Treatment	Soil properties				Available nutrient (kg/ha)					
	OC (%)		pH		N		P		K	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
T1	1.03	1.01	5.17	5.14	238.3	236.7	15.8	16.2	283.3	281.3
T2	1.14	1.12	5.20	5.16	267.2	260.8	18.6	17.4	287.7	284.6
T3	1.13	1.12	5.19	5.15	256.7	251.3	16.2	16.8	273.7	269.9
T4	1.13	1.11	5.18	5.15	252.8	253.3	16.3	16.9	271.8	267.3
T5	1.14	1.13	5.18	5.16	263.5	261.8	19.5	18.3	276.4	273.3
T6	1.12	1.11	5.17	5.15	255.3	256.7	16.6	15.9	278.1	275.6
T7	1.14	1.13	5.18	5.16	261.8	260.7	16.2	15.8	280.3	277.3
T8	1.13	1.11	5.17	5.14	265.3	264.2	17.8	16.7	279.5	279.1
T9	1.14	1.13	5.19	5.16	268.5	269.3	16.1	16.2	281.3	269.8
T10	1.13	1.12	5.18	5.15	259.4	258.7	16.7	16.9	274.9	269.5

Nano-urea treatments also improved the post-harvest soil OC (1.14% in 2022) and available N (261.8 kg ha^{-1} in 2022 & 269.3 kg ha^{-1} in 2023), particularly T7 and T9 respectively, compared to the control (236.7 kg ha^{-1} in 2023) Table 4.

Discussion

Growth attributes

It was found that, T7 (75% recommended dose of N + nano-urea at 6 mL L^{-1}) recorded the highest plant height (300.83 cm), significantly outperforming the other treatments. The greater plant height could be due to the higher nutrient availability during the early vegetative and crop establishment stages, which supported vigorous growth. Particularly, nitrogen is crucial as it enhances photosynthesis and protein formation, processes that stimulate cell division and elongation, ultimately resulting in faster and taller vegetative growth. These findings are in accordance with the results of Rundan et al. (2023) and Shekara et al. (2024). The leaf-to-stem ratio was found to be maximum in T5 (1.44). The increase in leaf: stem ratio with additional levels of nitrogen through foliar application of nano-urea @ 4 mL L^{-1} and 6 mL L^{-1} was mainly due to rapid expansion of dark green foliage, which could intercept and utilize the incident solar radiation in the production of photosynthates and eventually resulting in higher meristematic activity and increased leaf: stem ratio of fodder maize. These results conform with findings of Khinchi et al. (2017) and Lagad et al. (2020).

Yield performance

A significantly higher green fodder yield of maize of 525.39 q ha^{-1} and dry matter yield of 120.66 q ha^{-1}) was recorded with the application of 75% Recommended dose of N + nano-urea @ 6 mL L^{-1} (T7) over other N levels. The increase in the green fodder yield with a higher dose of nitrogen may be attributed to its increased nitrogen uptake, which directly contributes to photosynthesis as a constituent of chlorophyll pigment. This, in turn, facilitates higher crop growth rates and greater accumulation of dry matter. The superiority of nano-urea is attributed to its better penetration and utilization efficiency, consistent with earlier reports (Sudha et al., 2023; Srivani et al., 2023). Our findings also align with those of Gopinath et al. (2025), who reported that up to 25% of the recommended nitrogen dose can be curtailed without a yield penalty when supplemented with nano-urea. Overall, the data indicate that the foliar application of nano-urea significantly improved green fodder yield and dry matter yield, with T7 emerging as the most effective and efficient treatment among all other treatments.

Quality parameters

T9 showed a significantly higher crude protein content (10.75%). The application of 75% Recommended dose of N + nano-urea @ 6 mL L^{-1} (T7) showed significantly higher crude protein yield (11.82 q ha^{-1}) and was found on par with RDF (T2: 11.03 q ha^{-1}). Similar results are also reported by Shekara et al. (2015), Sewhag et al. (2021), and Arun Kumar et al. (2024).

Economics

Higher gross and net returns were obtained with a 75% recommended dose of N + nano-urea at 6 mL L^{-1} (T7) (₹1,05,078 ha^{-1} and ₹64,208 ha^{-1}, respectively and the highest benefit–to–cost (B:C) ratio was observed with RDF (T2: 2.61). Applying higher levels of nitrogen, possibly due to improved nitrogen use efficiency (NUE), boosted the yield of fodder maize and thereby increased economic returns. The greater profitability observed with nano-urea treatments can be linked to reduced fertilizer costs while still maintaining good yields.

Soil fertility

Among all the treatments, soil pH remained stable (≈5.15), which indicates that no adverse effects were incurred on the soil. Hence, it was concluded from these results that nano-urea improves nutrient recycling and maintains soil health.

Correlation analysis

The correlation matrix showed that most parameters of productivity and economy were positively related in fodder maize under nano-urea treatment, indicating the interrelationship between growth, yield, and profitability responses to the application of nano-urea. Plant height had extremely high correlations with green fodder yield (r = 0.88), dry matter yield (r = 0.87) and economic returns (r = 0.88 and r = 0.87 to gross and net economic returns, respectively) (Figure 2), indicating that the taller the plant, the better the fodder biomass production and economic returns under nano-urea treatments. The economic parameters demonstrated very strong intercorrelations, with green fodder yield and net returns demonstrating an almost perfect correlation (r = 0.99), and the B:C ratio was strongly associated with both green fodder yield (r = 0.95) and net returns (r = 0.98), such that treatments that increased productivity increased economic viability directly.

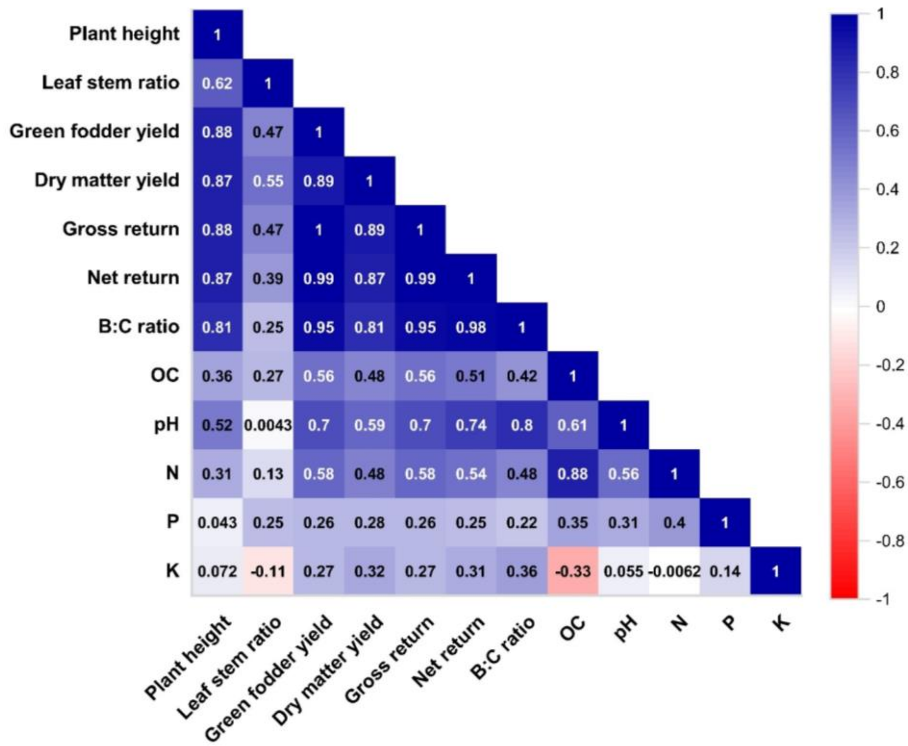

Figure 2. Correlation analysis between plant attributes, soil properties, and nano-urea effects on forage maize soil nutrients

Parameters of soil fertility were significantly or moderately correlated with productivity parameters, and organic carbon showed positive correlation with green fodder yield (r = 0.56) and economic returns (r = 0.51-0.56). Therefore, besides having direct productivity enhancing effects, the use of nano-urea also showed signs of enhancing soil health with the lapse of time. It is also important to note that there were significant positive correlations between soil pH and economic parameters (r = 0.70-0.80), implying that nano-urea could possibly also be used to alleviate soil acidity, thus boosting productivity. Available phosphorus and potassium were less correlated with the majority of parameters which indicate that it is the application of nano-urea that contributed more to the performance and that supported the finding that the application of nano-urea in an optimized manner (namely T7 treatment) constitutes an integrated solution to sustainable fodder maize production in terms of both yield and economic production and the replenishment of soil properties.

Principal component analysis

The PCA biplot demonstrated that the first and second components accounted for 73.5 percent of the total variance in the data (PC1: 59.5%, PC2: 14.0%) (Table 5), indicating that when the data are reduced in dimension, there is a high level of variance reduction and separation between nano-urea treatments in fodder maize performance. The green fodder yield, dry matter yield, gross return, net return, B:C ratio, and plant height loading were primarily captured in the first component, indicating a significant relationship. There is a strong intercorrelation among the parameters representing productivity and economic parameters. Treatments T3, T5, T9 exhibit an outstanding presence in the positive quadrant of PC1 (Figure 3), clearly demonstrating its performance excellence across most productivity and economic parameters, which fall short when compared to the challenge posed by T2 and T3. The types of components with a significant impact on the value of PC 2 were mainly the soil fertility parameters, which include organic carbon, available nitrogen, and phosphorus, all of which showed positive loading. Additionally, a positive loading for pH indicated that T3, T5, and T9 depicted enhanced representations of soil health benefits. T1 (control) appeared in the quadrant of poor performance across all parameters due to low productivity, whereas T2 (RDF) was grouped closer to productivity variables but still did not cluster together with T7 (conventional fertilization), indicating the additional benefits of nano-urea application compared to conventional one. The biplot is substantial in representing the multidimensional advantages of nano-urea technology at a smaller scale. The nano-urea treatment, optimized suitably (T7), offers multiple benefits in terms of productivity, economic returns, and soil fertility preservation, lending weight to the argument that nano-fertilizers present a sustainable solution for intensive fodder production systems.

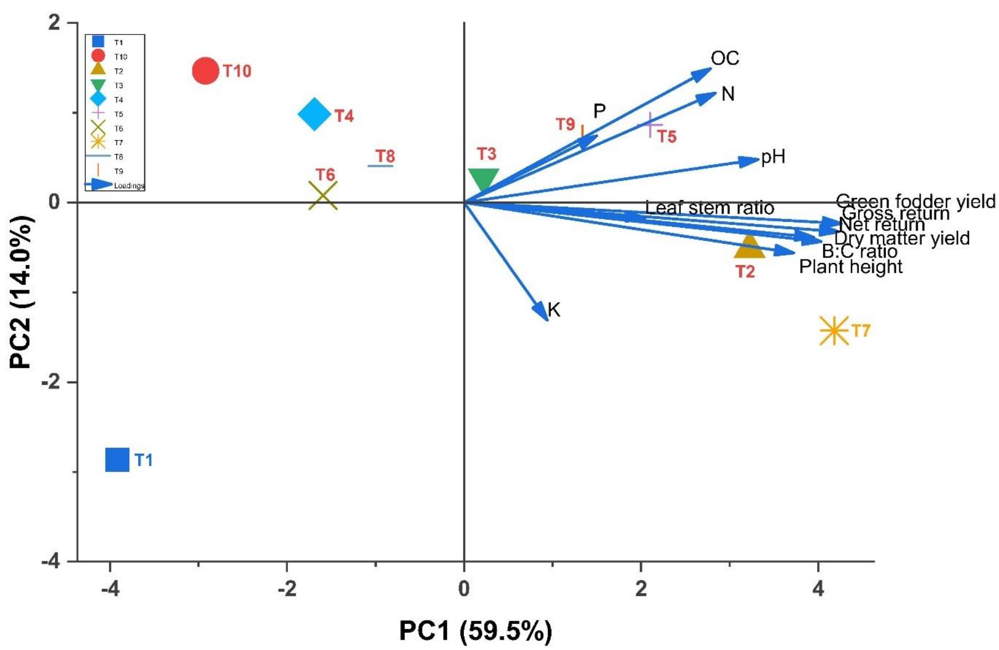

Figure 3. Biplot through principal component analysis between plant attributes, soil properties, and nano-urea effects on forage maize soil nutrients

Table 5. Eigenvalues and variance contribution through principal component analysis

PCA	Eigenvalue	Percentage of Variance (%)	Cumulative (%)
1	7.14434	59.53613	59.53613
2	1.68483	14.04024	73.57636
3	1.29904	10.82533	84.40169
4	1.0093	8.4108	92.81249
5	0.50339	4.1949	97.00739
6	0.17206	1.43382	98.44121
7	0.11546	0.96217	99.40338
8	0.06524	0.54367	99.94705
9	0.00635	0.05295	100
10	6.13E-31	5.11E-30	100

Conclusion

The pooled results, based on a 2-year study, indicated that the application of 75% RDN + foliar nano-urea @6 mL L^{-1} (T7) significantly improved fodder maize growth, yield, crude protein yield, economics, and soil fertility under subtropical, acidic soils in Imphal. These findings prove that nano-urea can reduce chemical nitrogen application by 25% without yield loss, offering a sustainable strategy for fodder production. Overall, the adoption of nano-urea can result in enhanced nitrogen use efficiency, improved economic returns, and greater environmental sustainability in fodder-based cropping systems.

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Author contributions

R. Joseph Koireng: Conception and Design, Supervision, Sonam Lhamu: Analysis and Interpretation of Data, Writing Publication, Konjengbam Maheshwari: Visualisation and Language Editing, Tanu Oinam: Analysis and Interpretation of Data, Writing Publication, Critical Revision of Publication, Osi Siram: Data Acquisition, Writing Publication, G K Dinesh: Review, Editing, Analysis, Software and Writing.

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Conflict of interest

The authors declare no conflict of interest. The manuscript has not been submitted for publication in any other journal.

Ethics approval

Not applicable.

AI tool usage declaration

The authors declare that no AI and associated tools are used for writing scientific content in the article.

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