RESEARCH ARTICLE Indian Journal of Animal Research, Volume 59 Issue 11: 1856-1864 (November 2025)

Enhancing Animal Nutritional Security Through Biofortification of Fodder Maize using Nano Urea Plus and Nano Zinc Oxide

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10.18805/IJAR.B-5623

ABSTRACT

Background: Rising demand for nutrient-rich fodder has highlighted the need for sustainable forage systems. In India, despite being the world's largest milk producer, fodder shortages, particularly a 61.1% deficit in green fodder, limit livestock productivity and milk yields. Maize (*Zea mays* L.) is a key fodder crop, but its yield and quality suffer due to nutrient deficiencies and inefficient fertilization. Conventional fertilizers contribute to nutrient loss and environmental issues, while Nano fertilizers offer better efficiency and forage quality. This study examines the effects of foliar-applied Nano Urea Plus and Nano ZnO on fodder maize to support sustainable livestock production.

Methods: The experiment was conducted during *Kharif* season of 2023-24, 2024-25 at Tamil Nadu Agricultural University; Coimbatore followed a randomized block design. The fodder maize crop was treated with three levels of Nano Urea (0.5%,0.75% and 1%) and two levels of Nano ZnO (50 ppm and 100 ppm), along with the recommended dose of fertilizers and an absolute control, resulting in nine unique treatment combinations.

Result: The study revealed that the combined application of 1% Nano Urea Plus and 100 ppm Nano ZnO along with the recommended dose of fertilizers significantly improved plant height (297.25 cm), the number of leaves (13.78), green fodder yield (437.04 q ha^{-1}) and dry fodder yield (101.70 q ha^{-1}) compared to absolute control. This treatment also enhanced forage quality by increasing crude protein content (9.70%), ether extract (2.56%) and total ash (9.19%), while reducing fibre fractions like neutral detergent fiber, acid detergent fibre, acid detergent lignin.

Key words: Crude protein content, Fodder maize, Forage quality, Nano fertilizers livestock productivity.

INTRODUCTION

The rising global demand for nutrient-dense livestock feed has underscored the need for sustainable and high-quality forage production systems (Shankar *et al.,* 2023). In India, the world's leading milk producer, the rapid expansion of cereal and cash crop cultivation has resulted in a substantial green fodder deficit of 61.1%, along with a declining availability of dry crop residues and concentrate feeds (Ajaykumar *et al.,* 2024). This feed scarcity directly affects livestock productivity, with average milk yields per cow remaining significantly lower than those in developed countries, largely due to limited access to high-quality fodder (Karthikeyan *et al.,* 2024). Green forages account for over 60% of the total cost of milk production, highlighting their critical role in the economic sustainability of dairy farming. Moreover, the country faces a 24.6% deficit in crude protein and a 19.9% shortfall in total digestible nutrients, with projections indicating continued shortages through 2030 and 2050 (IGFRI Vision, 2050). In this context, enhancing the yield, nutritional value and digestibility of fodder crops is imperative for improving feed efficiency and overall animal performance, ultimately contributing to increased milk and meat production in a sustainable manner.

Maize (*Zea mays* L.) is a key fodder crop due to its high biomass, palatability and carbohydrate content, making it essential in ruminant diets. However, it often lacks critical micronutrients like Zinc, Iron, Manganese and Copper, which are vital for livestock growth, reproduction and immunity. Deficiencies in these nutrients can impair animal performance and health (Rangasami *et al.,* 2024). Nitrogen is crucial for plant growth and forage quality, while zinc supports enzymatic functions, chlorophyll formation and

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How to cite this article: Purnima, M., Rangasami, S.R.S., Pushpam, R., Marimuthu, S., Prasad, V.B.R. and Ajaykumar, R. (2025). Enhancing Animal Nutritional Security Through Biofortification of Fodder Maize using Nano Urea Plus and Nano Zinc Oxide. *Indian Journal of Animal Research.* **59(11):** 1856-1864. doi: 10.18805/IJAR.B-5623.

Submitted: 09-05-2025 **Accepted:** 20-06-2025 **Online:** 07-07-2025

overall plant and animal health. Traditional fertilizers suffer from inefficiencies and environmental losses, prompting interest in Nano fertilizers (Choudhary *et al.,* 2018). These Nanoscale formulations offer controlled release, improved uptake and higher nutrient use efficiency up to 80% compared to 30-40% with conventional fertilizers (Rudani *et al.,* 2018). Specifically, Nano nitrogen promotes vegetative growth and protein content, while Nano zinc enhances stress tolerance, digestibility and micronutrient balance, collectively improving fodder maize yield and quality for better livestock nutrition (Kumar *et al*., 2021).

In this context, the present study aims to evaluate the effect of foliar application of Nano Urea Plus and Nano ZnO on the growth, yield and forage quality of fodder maize. The findings are expected to provide critical insights into the role of nano fertilizers in improving forage nutritive value and supporting sustainable, cost-effective strategies for better livestock nutrition, health and performance.

MATERIALS AND METHODS

The field experiment was carried out in *Kharif* season of the year 2023-24, 2024-25 at the F Block of the New Area Farm, Department of Forage Crops, Tamil Nadu Agricultural University, Coimbatore. The farm is located in the North western agro-climatic zone of Tamil Nadu at latitude of 11°N, longitude of 77°E and an altitude of 426.7 meters above mean sea level. The experimental field's soil was characterized as sandy clay loam with pH and EC of 8.54 and 0.43 dSm^{-1}. Chemical analysis revealed that the soil organic carbon content was measured at 0.51%, was medium in available nitrogen (202 kg ha^{-1}), medium in available phosphorus (15 kg ha^{-1}) and high in available potassium (628.0 kg ha^{-1}).

Experimental treatment details

The experiment was designed in a Randomized Block Design with three replications. (T_1: Absolute control (No application of fertilizers); T_2: RDF; T_3: Foliar application of Nano Urea Plus of 0.5%+Foliar application of Nano ZnO of 50 ppm; T_4: Foliar application of nano urea plus of 0.5%+ Foliar application of Nano ZnO of 100 ppm; T_5: Foliar application of nano urea plus of 0.75% + Foliar application of Nano ZnO of 50 ppm; T_6: Foliar application of Nano Urea Plus of 0.75%+ Foliar application of Nano ZnO of 100 ppm; T_7: Foliar application of nano urea plus of 1% + Foliar application of Nano ZnO of 50 ppm; T_8: Foliar application of nano urea plus of 1% + Foliar application of Nano ZnO of 100 ppm). The RDF of 60 kg Nitrogen ha^{-1}, 40 kg Phosphorus ha^{-1} and 20 kg Potassium ha^{-1} through Urea, single super phosphate (SSP) and Muriate of potash (MOP) were applied to all the treatments except T_1. A basal dose consisting of half the nitrogen and the complete doses of phosphorus and potassium was applied, followed by the remaining nitrogen split application at 30 days after sowing (DAS). The foliar sprays of Nano urea plus and Nano ZnO were applied as two foliar sprays at 35 DAS and 50 DAS. The fodder maize variety African Tall was used with a seed rate of 40 kg/ha.

Sample collection and estimation of green and dry fodder yield

Green fodder samples were harvested at 65 days. The fresh weight of each sample was recorded immediately after collection and the samples were then dried to constant weight in a hot air oven at 65±5°C. Once completely dried, the samples were weighed to determine the dry fodder yield. The dried samples were finely ground using a Wiley mill and passed through a 40-mesh sieve, the ground samples were stored in airtight containers for further nutrient composition analysis.

Fodder quality analysis

The crude protein (CP), total Ash and the ether extract (EE) were estimated as per A.O.A.C. (2005). Neutral detergent fibre, Acid detergent fibre, Acid detergent Lignin were determined, following the method outlined by VanSoest and Goering (1970).

Statistical analysis

The significance of different treatments was analyzed using the analysis of variance (ANOVA) technique. To compare treatment means, the least significant difference (LSD) test at $P \leq 0.05$ was employed, utilizing the GRAPES (General R-based Analysis Platform Empowered by Statistics) software. Correlation analysis was performed using the R software.

RESULTS AND DISCUSSION

Growth parameters

The growth performance of fodder maize, in terms of plant height, number of leaves per plant and leaf-to-stem ratio (LSR), was markedly enhanced by the foliar application of Nano urea plus and Nano ZnO. These parameters, essential for assessing vegetative growth, biomass accumulation and forage quality, demonstrated significant improvements with the application of Nano nutrients. Table 1 presents the data on growth parameters recorded at the harvest stage in fodder maize during the two years. The foliar application of 1% Nano Urea Plus combined with 100 ppm Nano ZnO (T_8) recorded maximum mean plant height, number of leaves per plant and leaf stem ratio of 297.25 cm, 13.78 and 0.44 respectively. These parameters were statistically comparable to the combination of 1% Nano Urea Plus and 50 ppm Nano ZnO (T_7). In contrast, the absolute control, devoid of any fertilizer application (T_1), exhibited the shortest mean plant height (212.38 cm), lowest leaf count (10.93) and lowest LSR (0.28). These physiological improvements contribute to increased plant height and overall plant vigor. The increase in the number of leaves per plant and LSR might be attributed to enhanced nitrogen availability and its pivotal role in chlorophyll formation and protein synthesis, promoting leaf expansion and canopy development while zinc aids in auxin synthesis, boosting leaf proliferation and vegetative growth.

Table 1: Effect of foliar application of nano urea plus and nano zinc oxide on plant height, no. of leaves plant^{-1} and leaf stem ratio of fodder maize.

Treatments	Plant height (cm)			No. of leaves plant^{-1}			Leaf stem ratio		
	2023-24	2024-25	Mean	2023-24	2024-25	Mean	2023-24	2024-25	Mean
T_1: Absolute control (No application of fertilizers)	218.77	206.99	212.38	11.04	10.81	10.93	0.29	0.28	0.28
T_2: Recommended dose of fertilizers (Fodder maize 60:40:20 NPK kg/ha)	248.72	236.75	242.73	12.02	11.96	11.99	0.33	0.32	0.32
T_3: Foliar application of nano urea of 0.5% + Foliar application of nano ZnO of 50 ppm	261.84	249.42	255.63	12.33	12.14	12.23	0.35	0.34	0.34
T_4: Foliar application of nano urea of 0.5% + Foliar application of nano ZnO of 100 ppm	267.32	261.54	264.43	12.39	12.28	12.33	0.36	0.35	0.35
T_5: Foliar application of nano urea of 0.75% + Foliar application of nano ZnO of 50 ppm	278.18	272.45	275.31	12.48	12.39	12.43	0.38	0.37	0.37
T_6: Foliar application of nano urea of 0.75% + Foliar application of nano ZnO of 100ppm	285.41	279.98	282.69	12.72	12.65	12.68	0.40	0.39	0.39
T_7: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 50 ppm	294.53	290.54	292.53	13.62	13.48	13.55	0.43	0.42	0.42
T_8: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 100 ppm	299.07	295.430	297.25	13.98	13.59	13.78	0.46	0.448	0.44
CD @ 5%	26.15	25.48	25.81	1.22	1.20	1.21	0.03	0.03	0.03
SE.d	12.19	11.88	12.03	0.57	0.56	0.56	0.01	0.01	0.01

The results of this study align with previous research in maize (Parameshnaik *et al.,* 2024).

Performance of green and dry fodder yield

The results demonstrated a significant increase in both green fodder yield (GFY) and dry fodder yield (DFY) with the application of Nano Urea Plus and Nano ZnO compared to the control and recommended dose of fertilizers and are presented in (Fig 1). Among the treatments, foliar application of 1% Nano Urea Plus + 100 ppm Nano ZnO (T_8) recorded the highest mean GFY (437.04 q ha^{-1}) and DFY (101.7 q ha^{-1}), which was statistically on par with 1% Nano Urea Plus + 50 ppm Nano ZnO (T_7), producing 431.58 q ha^{-1} and 97.94 q ha^{-1} of GFY and DFY, respectively. The lowest mean GFY and DFY of 300.70 q ha^{-1} and 37.08 q ha^{-1} recorded with no application of fertilizers. The GFY showed an increase of 45.34% and 17.42% respectively compared to the treatments of no application of fertilizers and recommended dose of fertilizers (T_1). Nano-sized urea has improved leaf penetration, increasing the nutrient uptake and efficiency of its use. It boosts chlorophyll content, photosynthate and cell division, promoting vigorous growth and higher green fodder yield in maize (Rajesh *et al.,* 2022). Zinc acts as a co-factor for various enzymes involved in carbohydrate, protein and auxin metabolism, while also maintaining membrane integrity (Gonzalez *et al.,* 2019). The significant increase in fodder yield in plants treated with 1% Nano Urea Plus + 100 ppm Nano ZnO (T_8) is owing to enhanced nitrogen use efficiency and improved micronutrient availability, promoting vigorous vegetative growth and biomass accumulation. These results agree with recent studies that highlight the effectiveness of nano fertilizers in improving maize productivity (Kashyap *et al.,* 2023).

Forage quality parameters

Effect on crude protein, crude protein yield, total ash and ether extract

Crude protein (CP), ether extract (EE) and total ash (TA) were significantly influenced by different treatments. The data related to effect of Nano Urea Plus and Nano ZnO in fodder maize is given in Table 2. The maximum CP (9.7%) and CPY 9.91 q ha^{-1} were recorded in the foliar application of 1% Nano Urea Plus + 100 ppm Nano ZnO (T_8). However, it was found statistically on par with the foliar application of 1% Nano Urea Plus + 50 ppm Nano ZnO (T_7) while the lowest values of CP (6.93%) and CP (2.57 q ha^{-1}) were observed in the absolute control (T_1).

The application of Nano Urea Plus and Nano ZnO considerably impacts the EE and TA content in fodder maize. Among the treatments, the highest mean EE (2.56%) was recorded with the foliar application of 1% Nano Urea Plus and 100 ppm Nano ZnO (T_8), followed closely by (T_7) 1% Nano Urea Plus and 50 ppm Nano ZnO (2.44%). In contrast, the lowest EE content (1.31%) was observed in the control treatment (T_1), which did not receive any fertilizer application. Similarly, the maximum mean TA (9.19%) was observed in the treatment with 1% Nano Urea Plus and 100 ppm Nano ZnO (T_8), which was statistically comparable to 1% Nano Urea Plus and 50 ppm Nano ZnO (8.99%) (T_7). On the other hand, the lowest TA (6.85%) was recorded in the control treatment (T_1). EE represents the lipid content of fodder and plays a crucial role in enhancing the energy density and digestibility of animal feed. Ether extract referred to as crude fat, can serve as a concentrated energy source for livestock growth, maintenance and overall performance. However, the digestibility of EE varies among different feed sources, directly impacting nutrient absorption, weight gain and feed conversion ratios in cattle, as energy-rich concentrates support better growth rates (Liman *et al.,* 2023).

The increased TA content observed in T_8 may be attributed to the enhanced accumulation of essential minerals such as phosphorus, potassium, copper and manganese, facilitated by the positive interaction of zinc with nitrogen and its role in improving mineral uptake in plants (Rajendra *et al.,* 2016). Higher mineral concentrations in fodder directly contribute to improved livestock nutrition by supporting vital physiological functions, bone development, enzyme activation and overall metabolic health, ultimately leading to better growth performance, reproductive efficiency and disease resistance in animals.

Effect on fibre fractions

The application of higher concentrations of Nano Urea and Nano ZnO led to a slight decrease in crude fibre (CF) content. The minimum CF of 28.95% was recorded in T_8, while the maximum CF of 36.67% was observed in T_1. The significant reduction in fibre fractions, including acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL), were noted in treatments receiving higher concentrations of foliar nano-fertilizers (Table 3). Specifically, the lowest ADF (36.66%), NDF (57.56%) and ADL (5.01%) were observed in plants treated with 1% Nano Urea Plus and 100 ppm Nano ZnO (T_8). This was comparable to the treatment with 1% Nano Urea Plus and 50 ppm Nano ZnO (T_7). Conversely, the highest values for ADF (45.91%), NDF (69.44%) and ADL (6.42%) were found in the absolute control treatment (T_1). These results suggest that the application of Nano Urea Plus and Nano ZnO reduces fibre fractions in fodder maize, likely due to the enhanced nutrient uptake and utilization efficiency enabled by the nano fertilizers. The higher fibre content in T_8 could be attributed to the structural development of plant tissues, which is enhanced by balanced nutrient availability (Dey *et al.,* 2024). Moreover, the foliar application of nano-fertilizers likely contributed to the robust formation of cell walls, which may explain the increased crude fibre content. Interestingly, the hemicellulose (HC) content remained non-significant among the treatments across both seasons. The effect of Nano Urea Plus and Nano ZnO in ADF, fodder maize is shown below (Fig 1). The data related to CPY and CFY is furnished in (Fig 1).

Table 2: Effect of foliar application of nano urea plus and nano zinc oxide on crude protein, ether extract and total ash of fodder maize.

Treatments	Crude protein (%)			Ether extract (%)			Total ash (%)		
	2023-24	2024-25	Mean	2023-24	2024-25	Mean	2023-24	2024-25	Mean
T_1: Absolute control (No application of fertilizers)	6.86	7.03	6.93^{d}	1.337	1.29	1.31^{d}	6.93	6.78	6.85^{c}
T_2: Recommended dose of fertilizers (Fodder maize 60:40:20 NPK kg/ha)	8.05	7.82	7.93^{c}	1.680	1.59	1.63^{c}	7.46	7.23	7.34^{de}
T_3: Foliar application of nano urea of 0.5%+ Foliar application of nano ZnO of 50 ppm	8.38	8.28	8.33^{bc}	1.730	1.68	1.70^{c}	7.92	7.69	7.80^{cd}
T_4: Foliar application of nano urea of 0.5%+ Foliar application of nano ZnO of 100 ppm	8.62	8.56	8.59^{bc}	1.770	1.71	1.74^{c}	8.11	7.98	8.04^{bcd}
T_5: Foliar application of nano urea of 0.75% + Foliar application of nano ZnO of 50 ppm	8.94	8.81	8.87^{ab}	1.840	1.79	1.81^{bc}	8.47	8.36	8.41^{abc}
T_6: Foliar application of nano urea of 0.75%+ Foliar application of nano ZnO of 100 ppm	9.18	9.05	9.11^{ab}	1.980	1.93	1.95^{b}	8.78	8.54	8.66^{ab}
T_7: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 50 ppm	9.53	9.38	9.45^{a}	2.460	2.42	2.44^{a}	9.08	8.91	8.99^{a}
T_8: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 100 ppm	9.79	9.61	9.70^{a}	2.540	2.59	2.56^{a}	9.26	9.13	9.19^{a}
CD @ 5%	0.84	0.83	0.84	0.19	0.19	0.19	0.80	0.78	0.79
SE.d	0.39	0.38	0.39	0.09	0.09	0.09	0.37	0.36	0.37

Table 3: Effect of foliar application of nano urea plus and nano zinc oxide on fibre fractions of fodder maize.

Treatments	Crude fibre (%)			NDF (%)			ADF (%)			Hemi cellulose (%)			ADL (%)		
	2023-24	2024-25	Mean	2023-24	2024-25	Mean	2023-24	2024-25	Mean	2023-24	2024-25	Mean	2023-24	2024-25	Mean
T_1: Absolute control (No application of fertilizers)	36.90	37.00	36.67	69.07	5.96	69.44	45.08	46.73	45.91	23.98	23.62	23.52	6.26	6.58	6.42
T_2: Recommended dose of fertilizers (Fodder maize 60:40:20 NPK kg/ha)	34.70	35.12	34.91	65.80	2.77	66.00	42.40	42.58	42.49	23.4	23.16	23.51	6.03	6.19	6.11
T_3: Foliar application of nano urea of 0.5%+ Foliar application of nano ZnO of 50 ppm	33.30	34.25	33.75	64.57	5.96	64.83	41.57	41.94	41.75	23	23.07	23.08	5.74	5.96	5.85
T_4: Foliar application of nano urea of 0.5%+ Foliar application of nano ZnO of 100 ppm	32.60	33.72	33.16	63.81	2.77	63.94	41.11	41.63	41.37	22.7	22.74	22.57	5.69	5.81	5.75
T_5: Foliar application of nano urea of 0.75% + Foliar application of nano ZnO of 50ppm	31.80	32.62	32.21	63.05	5.96	63.40	40.75	41.02	40.88	22.3	22.45	22.52	5.56	5.63	5.59
T_6: Foliar application of nano urea of 0.75%+ Foliar application of nano ZnO of 100 ppm	31.10	31.56	31.33	62.23	2.77	62.59	40.43	40.89	40.66	21.8	22.06	21.93	5.42	5.54	5.48
T_7: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 50 ppm	29.90	30.08	29.99	58.29	5.96	58.6	37.09	37.45	37.27	21.2	21.46	21.33	5.18	5.28	5.23
T_8: Foliar application of nano urea of 1% + Foliar application of nano ZnO of 100 ppm	28.70	29.21	28.95	57.28	2.77	57.56	36.38	36.94	36.66	20.9	20.91	20.90	5.03	5.11	5.07
CD @ 5%	3.04	3.09	3.067	5.93	5.98	5.96	3.81	3.86	3.84	NS	NS	NS	0.52	0.54	0.53
SE.d	1.41	1.44	1.430	2.77	2.79	2.77	1.77	1.80	1.79	0.98	0.98	0.98	0.24	0.25	0.24

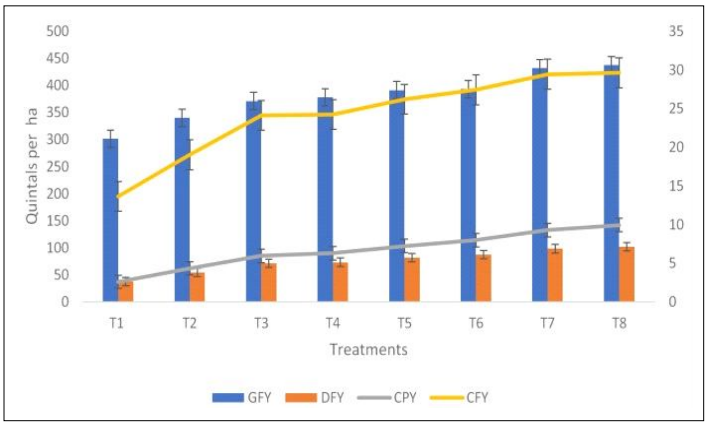


Fig 1: Effect of foliar application of nano urea plus and nano zinc oxide on green fodder, dry fodder and crude protein yield of fodder maize.

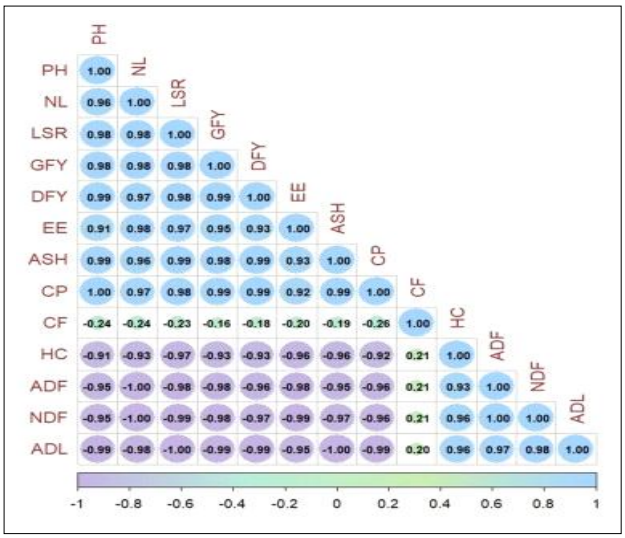


Fig 2: Correlation plot illustrating the relationship between growth, yield and quality parameters of fodder maize.

Bhaumik and Rajeev (2024) reported similar findings, noting an increase in CF, ADF, NDF and ADL contents in fodder maize treated with Nano Urea and Nano ZnO. Studies have also shown that lower NDF levels in animal diets can significantly enhance the digestibility of dry matter (DM) and organic matter (OM) in cattle (Truong and Tuan, 2023). In ruminants, reduced fibre levels contribute to more efficient rumen fermentation, leading to higher volatile fatty acid production and better nitrogen utilization (Zhou *et al.,* 2022). Thus, the application of nano-fertilizers not only improves crop quality but also has potential benefits for animal nutrition by increasing feed digestibility and enhancing nutrient absorption.

Correlation analysis

The correlation matrix plot demonstrated the impact of foliar application of Nano urea and Nano ZnO on fodder growth, quality and yield parameters (Fig 2). Foliar application of Nano Urea and Nano ZnO significantly enhances plant height and the number of leaves as indicated by their strong positive correlation (r = 0.96), suggesting that the synergistic effect of nitrogen and zinc promotes vigorous vegetative growth. Moreover, the increased CP exhibits a strong positive correlation with GFY and DFY (r= 0.99), highlighting that improved nitrogen assimilation through Nano Urea contributes to higher protein synthesis and biomass production. Additionally, the combination of Nano Urea and Nano ZnO reduces the fiber content, as evident from the negative correlation of CP with ADF and NDF, indicating better digestibility and forage quality. Furthermore, the moderate positive correlation between EE and TA suggests that the enhanced nutrient availability from Nano ZnO improves fat content and mineral accumulation. Overall, foliar application of Nano Urea Plus and Nano ZnO positively influences both fodder yield and quality, making it an effective strategy for improving forage productivity. Similar results were also observed by (Kumar *et al.*, 2023).

CONCLUSION

The results demonstrated that foliar application of 1% Nano Urea Plus and 100 ppm Nano ZnO at 35 and 50 DAS significantly improved biomass yield and forage quality of fodder maize, marked by higher crude protein and ether extract content and lower fibre fractions. This enhancement in nutritional composition directly benefits livestock by supporting better feed intake, improved digestibility and higher nutrient availability, which are crucial for optimal animal growth, health and productivity. The synergistic effect of nano nitrogen and zinc not only boosts nutrient uptake and vegetative growth but also contributes to more efficient nutrient cycling. By minimizing nutrient losses and reducing dependence on conventional fertilizers, nano fertilizers offer a promising pathway toward sustainable livestock production systems and improved feed efficiency.

Conflict of interest

All authors declared that there is no conflict of interest.

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