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Quantitative and Qualitative Response of Fodder Maize to Use of Bulk and Nano-fertilizers in North Western Plains of India

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Abstract: Optimizing nutrient management strategies is crucial for enhancing the growth, yield, and nutritional quality of fodder maize (*Zea mays*) while minimizing environmental impacts. This study investigated the effects of innovative nitrogen (N) and zinc (Zn) management approaches on fodder maize production. Different combinations of nitrogen fertilizers, including conventional urea and nano-urea, were applied in conjunction with targeted foliar sprays of zinc sulfate ($ZnSO_4$) and nano-zinc. The experiment was carried out in a Factorial Randomized Block design with four nitrogen management strategies (control N, 100% recommended nitrogen dose RDN through urea, 50% RDN through urea + two sprays of nano-urea at six and ten leaves stages, and 33.33% RDN through urea + two sprays of nano-urea at six and ten leaves stage) and four zinc management strategies (control Zn, soil application of $ZnSO_4$, foliar application of $ZnSO_4$, and foliar application of nano-Zn) which were replicated thrice. The study revealed that applying 50% of RDN through urea, along with dual foliar sprays of nano-urea, achieved comparable productivity to the 100% RDN through urea only. Among the Zn managements, both foliar and soil applications of conventional $ZnSO_4$ recorded similar green and dry fodder yields, although foliar application of $ZnSO_4$ was observed to be superior in terms of qualitative attributes. Maize subjected to the integrated nitrogen and zinc management strategy exhibited elevated protein content and reduced fiber fractions. These findings highlight the potential of nano-urea and foliar zinc application in enhancing both productivity and nutritional quality, while reducing dependence on conventional chemical fertilizers.

Keywords: fodder maize; nutrient management; yield; fodder quality; nano-fertilizer

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1. Introduction

Livestock sustains and boosts agriculture in most farming systems. India feeds about 20% of the world's livestock and 17.5% of its people on only 2.3% of the world's land [1]. The human and livestock populations are increasing at a pace of 1.6 and 0.66% per annum. These increasing human and animal populations are competing for food and fodder resources, respectively, on the restricted land resources. Presently, cultivation of fodders is limited to only 4% of the entire cultivable land in the country. The performance of livestock and the economics of milk production are heavily dependent on the quantity and quality of fodder fed to animals. There is a current shortfall of 35.6% green fodder, 10.5% dry fodder, and 44% concentrate feed ingredients across the country [2]. The opportunity for expanding the land area under fodder cultivation is very restricted. Consequently, it faces serious obstacles in optimizing the use of available land to provide sufficient and high-quality animal feed [1].

Under Indian conditions, green fodder is one of the most important components of animal nutrition. Maize (*Zea mays* L.) is well-known for producing a higher tonnage of quality fodder, as well as a greater tolerance to a wider range of climatic conditions [3]. It is an ideal fodder crop owing to its rapid growth, succulence, palatability, and excellent quality without any antinutritional quality substance throughout the growth stages of the crop. Maize being highly exhaustive, it demands good nutrient management [4]. Better quality fodder is important for milk production because it sends more crude protein and other nutrients to the small intestine. This improves the livestock's overall nitrogen balance [5]. Low availability of nutrient-rich feeds and fodder results in unhealthy animals and poorer dairy yield.

Nitrogen (N) is the key nutrient that determines the herbage yield and quality. Because maize is a cereal crop, its nitrogen demand is considerably high [6,7]. Nitrogen fertilization has been proven to positively correlate with fodder yield and quality of fodder maize [7–10]. Worldwide N deficiency is widespread, including in India [11]. The major source of N fertilizer in India is urea [12]. However, the typical use efficiency of nitrogen fertilizers like urea is about 30–40% in most agriculture fields [13]. The unutilized urea is released into the environment through various means and pollutes soil, air, and water. For instance, urea volatilizes in the form of nitrous oxide, a greenhouse gas, and emits in the form of ammonia contributing to global warming and air pollution [14]. The leached urea through the soil in the form of nitrate affects the drinking water quality [15]. Besides nitrogen, many researchers have reported zinc deficiency in soil all over the world [16–18]. In India, 51.2% of soils are deficient in zinc [11]. Direct linkages between available micronutrients in the soil and their contents in forage and fodders have been widely studied and established and it is also common in the case of zinc [19–22]. Zinc is vital for plants, animals, and human nutrition. Therefore correcting the zinc deficiencies by supplementing fertilizers to crops will benefit both farmers (higher yields) and consumers (micronutrient-enriched food/fodder).

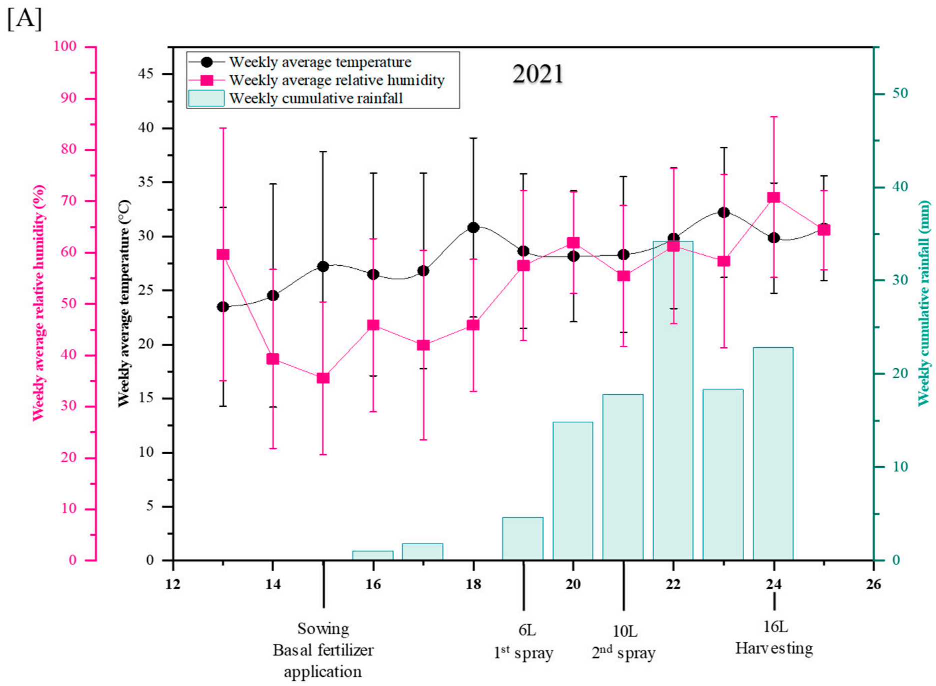
Currently, research into nanoscale or nanostructured materials as fertilizer carriers or controlled-release facilitates increased the nutrient use efficiency while lowering the cost of environmental contamination. [23]. Nano-fertilizers exhibit site-targeted delivery, reduced nutrient toxicity, controlled the release of agrochemicals, and improved the nutrient uptake of given fertilizers. These features are attributable to high solubility and specific targeting due to their small size, high mobility, and low toxicity of nanoforms [24]. Due to the undesirable effects on the environment, the use of chemical fertilizers has therefore long been criticized and alternatives must be investigated. It is anticipated that nanoparticles with small size and big surface area will make the best fertilizer options for crops to maximize fertilizer use efficiency and reduce the harmful impacts of fertilizers on the environment.

Therefore, an attempt was made to study the response of fodder maize in terms of fodder yield and quality to application of nano as well as bulk nitrogen and zinc fertilizers.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted in the years 2021 and 2022 at the Research Farm of the Agronomy Section, National Dairy Research Institute, Karnal, Haryana (India), which is situated at an elevation of 245 m above mean sea level in the sub-tropical zone at latitude 29°43′ N and longitude 76°58′ E. The experimental site's semi-arid climate was typified by scorching, dry summers and very frigid winters. Annual rainfall of the area varies from 690–720 mm with a bimodal distribution, over 70% of which occurs during the main rainy season (July to September) and 30% during the rest of the months, especially from February to April (Figure 1). The soil of the experimental block was well-drained clay loam (43.97, 21.43, and 34.60% of sand, silt, and clay respectively). The physicochemical properties of the initial soil sample is given in Table 1.



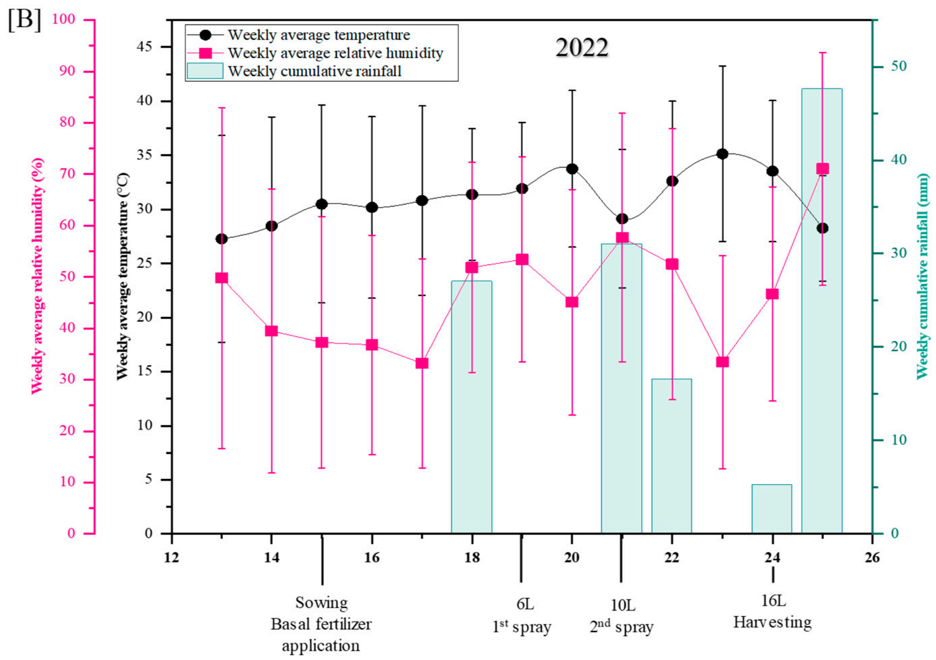


Figure 1. Weakly average temperature, weekly average relative humidity, and weekly cumulative rainfall during crop season of 2021 (**A**) and 2022 (**B**). (Note: X-axis indicates standard meteorological week and phenological stages of maize; weekly average temperature (°C) (black circle and connecting lines) and weekly average relative humidity (%) (pink square and connecting lines) are plotted on the left Y-axis while the weekly cumulative rainfall (mm) (bars of cyan color are plotted on the right Y-axis). The error bars of weekly average temperature and weekly average relative humidity indicate standard deviation between maximum and minimum values of the respective parameter. 6 L; six leaves stage; 10 L, ten leaves stage; 16 L, sixteen leaves stage of maize. Sowing as well as basal fertilizer application was conducted on the 15th standard meteorological week and harvesting was conducted at 16 leaves stage (24th meteorological week).

Table 1. Physicochemical properties of the initial soil sample.

Soil Properties	Soil Depth (cm)		
	0–15 cm	15–30 cm	30–60 cm
Bulk density (Mg m^{-1})	1.48	1.54	1.57
$pH_{1:2}$	7.5	7.7	7.8
$EC_{1:2}$ (dSm^{-1})	0.3	0.27	0.22
OC (%)	0.63	0.48	0.31
Available N (kg ha^{-1})	202.59	191.65	176.28
Available P (kg ha^{-1})	30.0	27.44	24.23
Available K (kg ha^{-1})	206.70	198.22	195.58
Available S (kg ha^{-1})	18.65	16.27	13.54
DTPA-extractable Zn (mg kg^{-1})	0.35	0.31	0.23

2.2. Experimental Treatment Details

The present study was carried out in factorial randomized block design (FRBD) with two factors that were replicated three times for two consecutive years in fodder maize. It included two factors i.e., factor A (N management) and factor B (Zn management). The details of the experiment are given in Table 2. The variety of fodder maize used here was J-1006. The fodder maize was grown in food–fodder cropping sequence i.e., wheat followed by fodder maize in both the study years. The same treatments were applied to both crops. The land was cross plowed with the help of tractor-drawn disc harrow followed by a rotavator and planking to bring the soil to a proper tilth. Then, bunds were made with tractor-drawn bund former for irrigation. In the experimental plots, we had used fertilizers at the dose of 120:26:33: N:P:K kg ha^{-1}. The sources of P and K fertilizers were single super phosphate and muriate of potash, respectively. The seed rate for fodder maize was 50 kg ha^{-1} for this experiment. The sowing was conducted in lines with a spacing of 30 cm between the rows and 5 cm between plants. The final plant population was 666,667 plants ha^{-1}. The sowing fodder maize was conducted on 15 April 2021 and 9 April 2022 in both years. Commercial nano-urea and nano-zinc fertilizers were obtained from Indian Farmers Fertilizer Cooperative Limited (IFFCO), which contained 4% and 1%, N and Zn, respectively. Foliar application of nano-fertilizers was conducted at 30 and 45 days after sowing (DAS), and the rest of the treatments were foliar applications with water, where nutrient is not applied to maintain the uniformity of spraying.

Table 2. Details of experimental treatments.

Factor A (N Management)		Factor B (Zn Management)	
Treatment Abbreviation	Treatment Details	Treatment Abbreviation	Treatment Details
N_0	Control (No Nitrogen)	Zn_0	control (No Zn)
N_1	Recommended dose of nitrogen (RDN) through urea	Zn_1	$ZnSO_4$ soil application @ 10 kg ha^{-1}
N_2	50% RDN (urea) + two sprays of nano-urea of 2000 ppp of N in each spray *	Zn_2	$ZnSO_4$ foliar application @ 0.5% or 2500 ppm of Zn on each spray (total two sprays) *
N_3	33.3% RDN (urea) + two sprays of nano-urea of 2000 ppm of N in each spray *	Zn_3	Nano-Zn foliar application @ 0.5% or 2500 ppm of Zn on each spray (total two sprays) *

P and K are applied to all the treatment as per the recommended dose. * at six leaves emergence stage (30 days after sowing) and ten leaves emergence' stage (45 days after sowing) of maize, respectively.

2.3. Sample Collection and Estimation of Green and Dry Fodder Yield

Fodder maize was harvested when the crop reached 50% flowering stage. To avoid the border effect, plants from border rows were harvested first; thereafter, the plants of the net plot area were harvested, and fresh forage yield was recorded. Green fodder samples of 500 g were dried in a hot air oven at 65 ± 5 °C till constant weight was attained. The loss in moisture content after drying was estimated, and then dry fodder yield was calculated. Thereafter, dried samples were ground to pass through 40 mesh sieves in a Macro-Wiley Mill and used for chemical analysis.

2.4. Fodder Quality Analysis

Quality (proximate) analysis was performed using the standard methods on all samples collected. The Kjeldahl technique was used to determine crude protein (CP) content of the samples. For distillation, KEL PLUSVR (Pelican, Chennai, India) N analyzer was used. Then, the obtained N content was multiplied by a factor of 6.25 to determine the CP (%). Total ash and ether extract were evaluated by standard methods by AOAC. Methods proposed by Van Soest, Robertson, and Lewis (1991) were used to calculate the relative amounts of cell wall components like neutral detergent fiber (NDF), acid detergent fiber (ADF), acid insoluble ash (AIA), and acid detergent lignin (ADL). There was no ash left over from the expression of either NDF or ADF. By deducting the ADF (%) from the NDF (%), hemicellulose contents were recorded in samples. Dry matter intake (DMI), dry matter digestibility (DMD), total digestible nutrients (TDN), relative feed value (RFV) [25], and relative feed quality (RFQ) [26] were determined by using the following formulae:

$$\text{Dry matter intake (\%): DMI} = 120/\text{NDF (\%)}$$

$$\text{Dry matter digestibility (\%): DMD} = 88.9 - (0.779 \times \text{ADF\%})$$

$$\text{Total digestible nutrients (\%): TDN} = (-1.291 \times \text{ADF\%}) + 101.35$$

$$\text{Relative feed value (\%): RFV} = (\text{DMI} \times \text{DMD})/1.29$$

$$\text{Relative feed quality (\%): RFQ} = (\text{DMI} \times \text{TDN})/1.23$$

2.5. Statistical Analysis

All data recorded for different parameters were analyzed with the help of analysis of variance (ANOVA) technique for factorial RBD design using the R statistical program R Studio 4.0.2 [27]. The mean significant difference test was used to interpret the main and interaction effects of treatments at 5% management of significance ($p < 0.05$) by using Tukey's HSD test. Correlation analysis was performed using R 4.2.1software and the significance of differences between means was determined at 0.05 and 0.01 probability management.

3. Results

3.1. Performance of Green and Dry Fodder Yield

The results showed that different nitrogen and zinc nutrient management strategies had a significant impact on the green fodder yield (GFY) and dry fodder yield (DFY) of fodder maize (Table 3). The study year did not affect the GFY and DFY significantly. Application of full dose of nitrogen through urea (N_1) was found to be significantly superior over control N and N_3 concerning GFY and DFY yield i.e., 63.50 and 15.55 t ha^{-1}, respectively, but statistically similar with N_2 (62.29 and 15.19 t ha^{-1}, GFY and DFY, respectively). The GFY and DFY enhancement with the application of N_1 was 59.99% and 77.11%; with the application of N_2, it was 56.94% and 73.01%, respectively, over the control (N_0). Among various zinc managements, foliar application of $ZnSO_4$ @ 0.5% i.e., Zn_2 (60.16 and

14.46 t ha^{-1}, respectively), and soil application of $ZnSO_4$ @ 10 kg ha (58.14 and 13.86 t ha^{-1}, respectively) recorded statistically similar GFY and DFY. The lowest GFY and DFY were observed under the control Zn treatment. Percentage increases in GFY and DFY with the application of Zn_2 were 25.52 and 29.10%, respectively, over the control and 9.48 and 11.57%, respectively, over Zn_3.

Table 3. Green fodder yield (GFY), dry fodder yield (DFY), crude protein (CP), total ash (TA), and ether extract (EE) the content of fodder maize as influenced by nitrogen and zinc managements.

Treatments	GFY (t ha^{-1})	DFY (t ha^{-1})	CP (%)	TA (%)	EE (%)
Year					
2020–2021	54.82	13.01	8.92	6.81	2.07
2021–2022	55.77	13.22	8.98	7.03	2.09
SEm(±)	0.50	0.12	0.02	0.08	0.01
MSD (p = 0.05)	NS	NS	NS	NS	NS
N Management					
N_0	39.69 ^{c}	8.78 ^{c}	7.08 ^{c}	6.03 ^{c}	1.84 ^{c}
N_1	63.50 ^{a}	15.55 ^{a}	9.79 ^{a}	7.49 ^{a}	2.18 ^{a}
N_2	62.29 ^{a}	15.19 ^{a}	9.70 ^{a}	7.47 ^{a}	2.17 ^{a}
N_3	55.73 ^{b}	13.01 ^{b}	9.22 ^{b}	6.70 ^{b}	2.05 ^{b}
SEm(±)	0.71	0.17	0.03	0.09	0.01
MSD (p = 0.05)	2.65	0.62	0.13	0.34	0.05
Zn Management					
Zn_0	47.93 ^{c}	11.20 ^{c}	8.78 ^{c}	6.26 ^{c}	1.96 ^{c}
Zn_1	58.14 ^{a}	13.86 ^{a}	8.99 ^{ab}	7.17 ^{ab}	2.09 ^{a}
Zn_2	60.16 ^{a}	14.46 ^{a}	9.08 ^{a}	7.37 ^{a}	2.14 ^{a}
Zn_3	54.95 ^{b}	12.96 ^{b}	8.94 ^{b}	6.90 ^{b}	2.03 ^{b}
SEm(±)	0.71	0.17	0.03	0.09	0.01
MSD (p = 0.05)	2.65	0.62	0.13	0.34	0.05
N × Zn					
SEm(±)	1.42	0.33	0.07	0.18	0.03
MSD (p = 0.05)	7.17	1.67	NS	NS	NS

Note: N_0: Control N, N_1: 100% RDN through urea, N_2:50% RDN through urea + two sprays of nano-urea, N_3: 33.33% RDN through urea + two sprays of nano-urea, Zn_0: control Zn, Zn_1: soil application of $ZnSO_4$, Zn_2: foliar application of $ZnSO_4$ and Zn_3: foliar application of nano-Zn. Same letters within each column indicate non-significant difference among the treatments using Tukey's HSD test (p < 0.05).

The interactive effect of various nitrogen and zinc managements on GFY and DFY was significantly affected (Figure 2). Statistically similar GFY and DFY were recorded under combined application of either application of 100% RDN through urea or N_2 with foliar application of $ZnSO_4$ or soil application of $ZnSO_4$ @ 10 kg ha^{-1} (Figure 2). Treatment combinations N_1Zn_2, N_2Zn_2, N_1Zn_1, and N_2Zn_1 recorded 70.38, 69.19, 67.58, and 66.39 t ha^{-1} of GFY, respectively, and 17.39, 17.10, 16.55, and 16.26 t ha^{-1} of DFY, respectively.

3.2. Quality Parameters

3.2.1. Effect on Crude Protein, Total Ash, and Ether Extract

The results indicating the effect of nitrogen and zinc management on crude protein, total ash content, and ether extract of fodder maize are given in Table 3. Both N_1 and N_2 recorded significantly higher and statistically at par content of CP (9.79 and 9.70%, respectively), total ash (7.49 and 7.47%, respectively), and EE (2.18 and 2.17%, respectively). However, the control recorded the lowest values of CP, TA, and EE. The application of $ZnSO_4$ as foliar and soil recorded significantly superior content of CP (9.08 and 8.99%, respectively), total ash (7.37 and 7.17%, respectively), and ether extract (2.14 and 2.09%, respectively) over N_0 and N_3.

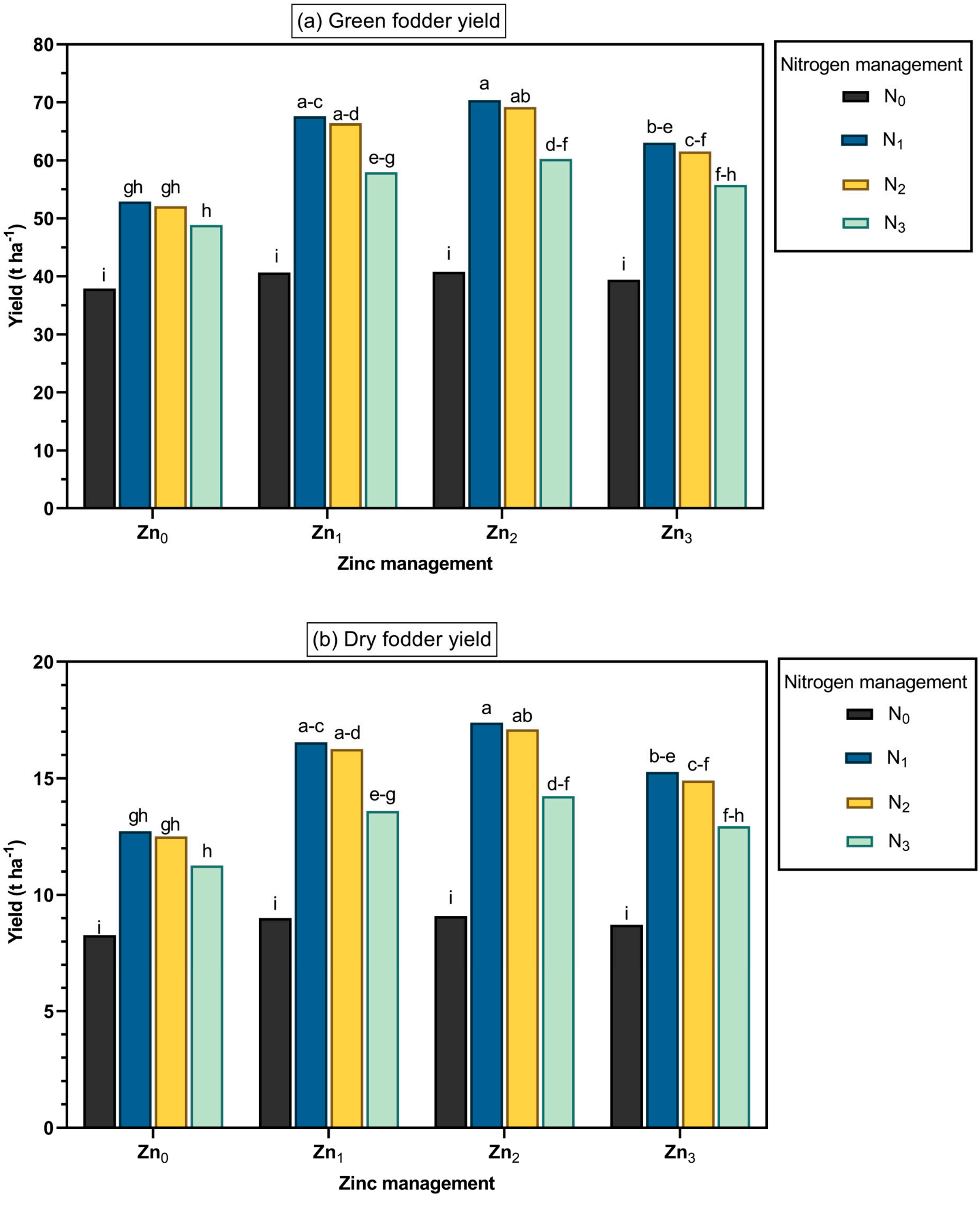


Figure 2. Interaction effect of N and Zn managements on green fodder yield (**a**) and dry fodder yield (**b**) Same letters indicate non-significant difference among the treatments using Tukey's HSD test ($p < 0.05$). Note: N_0: Control N, N_1: 100% RDN through urea, N_2:50% RDN through urea + two sprays of nano-urea, N_3: 33.33% RDN through urea + two sprays of nano-urea, Zn_0: control Zn, Zn_1: soil application of $ZnSO_4$, Zn_2: foliar application of $ZnSO_4$ and Zn_3: foliar application of nano-Zn.

3.2.2. Fiber Fraction

Quality parameters like NDF, ADF, hemicellulose, ADL, and AIA content (%) in fodder maize were affected significantly by N and Zn management. N_1 was found to be superior with lower content of NDF, ADF, hemicellulose, ADL, and AIA (%) i.e., 62.90, 42.11, 20.79, 5.01, and 1.46, respectively, which was statistically at par with N_2 i.e., 62.95, 42.29, 20.66, 5.04, and 1.46%, respectively (Table 3). Similarly, soil and foliar application of $ZnSO_4$ recorded statistically similar and lower values of NDF, ADF, hemicellulose, ADL, and AIA content in fodder maize (Table 4).

Table 4. Neutral detergent fiber (NDF), acid detergent fiber (ADF), hemicellulose (HC), acid detergent lignin (ADL), and acid insoluble ash (AIA) content of fodder maize as influenced by nitrogen and zinc managements.

Treatments	NDF (%)	ADF (%)	HC (%)	ADL (%)	AIA (%)
Year					
2020–2021	64.60	42.91	21.69	5.31	1.86 ^{a}
2021–2022	65.26	43.55	21.71	5.23	1.84 ^{b}
SEm(±)	0.18	0.15	0.17	0.03	0.004
MSD (p = 0.05)	NS	NS	NS	NS	0.12
N Management					
N_0	68.53 ^{a}	45.12 ^{a}	23.41 ^{a}	5.65 ^{a}	1.75 ^{c}
N_1	62.90 ^{c}	42.11 ^{c}	20.79 ^{c}	5.01 ^{c}	1.91 ^{a}
N_2	62.95 ^{c}	42.29 ^{c}	20.66 ^{c}	5.04 ^{c}	1.91 ^{a}
N_3	65.33 ^{b}	43.38 ^{b}	21.95 ^{b}	5.39 ^{b}	1.84 ^{b}
SEm(±)	0.20	0.21	0.25	0.04	0.01
MSD (p = 0.05)	0.74	0.77	0.92	0.14	0.02
Zn Management					
Zn_0	67.59 ^{a}	45.00 ^{a}	22.59 ^{a}	5.42 ^{a}	1.78 ^{d}
Zn_1	63.91 ^{c}	42.64 ^{c}	21.27 ^{b}	5.22 ^{b}	1.88 ^{b}
Zn_2	62.36 ^{d}	41.34 ^{d}	21.02 ^{b}	5.18 ^{b}	1.93 ^{a}
Zn_3	65.85 ^{b}	43.92 ^{b}	21.92 ^{ab}	5.26 ^{b}	1.83 ^{c}
SEm(±)	0.34	0.20	0.25	0.04	0.01
MSD (p = 0.05)	1.27	0.77	0.92	0.14	0.02
N × Zn					
SEm(±)	0.40	0.42	0.50	0.08	0.01
MSD (p = 0.05)	NS	NS	NS	NS	NS

Note: N_0: Control N, N_1: 100% RDN through urea, N_2:50% RDN through urea + two sprays of nano-urea, N_3: 33.33% RDN through urea + two sprays of nano-urea, Zn_0: control Zn, Zn_1: soil application of $ZnSO_4$, Zn_2: foliar application of $ZnSO_4$ and Zn_3: foliar application of nano-Zn. Same letters within each column indicate non-significant difference among the treatments using Tukey's HSD test ($p < 0.05$).

3.2.3. Correlation of GFY, DFY, and Quality Traits

Every possible correlation matrix on fodder yield and quality of maize is presented in Figure 3. The data show that the green fodder yield has a high positive correlation (at $p < 0.05$, 0.01) with DFY, CP, total ash, and ether extract, and a negative one with NDF, ADF, hemicellulose, and ADL.

3.2.4. Effect on Different Nutritional Indices

Fodder maize recorded noticeably higher DMD (56.10%), TDN (46.99%), RFV (83.19%), and RFQ (73.13%) recorded with the application of 100% RDN through urea (N_1). This N_1 was statistically at par with N_2 i.e., 55.10, 46.76, 82.75, and 72.56% DMD, TDN, RFV, and RFQ of fodder maize. Both N_1 and N_2 were significantly superior to N_0 and N_3. The control i.e., N_0 recorded the lowest value for the above digestibility indices. The significantly higher percentage of DMD (56.70), TDN (47.98), RFV (84.76), and RFQ (75.27) among various zinc management was obtained with twice the foliar application of $ZnSO_4$ @ 0.5% and the lowest with control zinc (Figure 4).

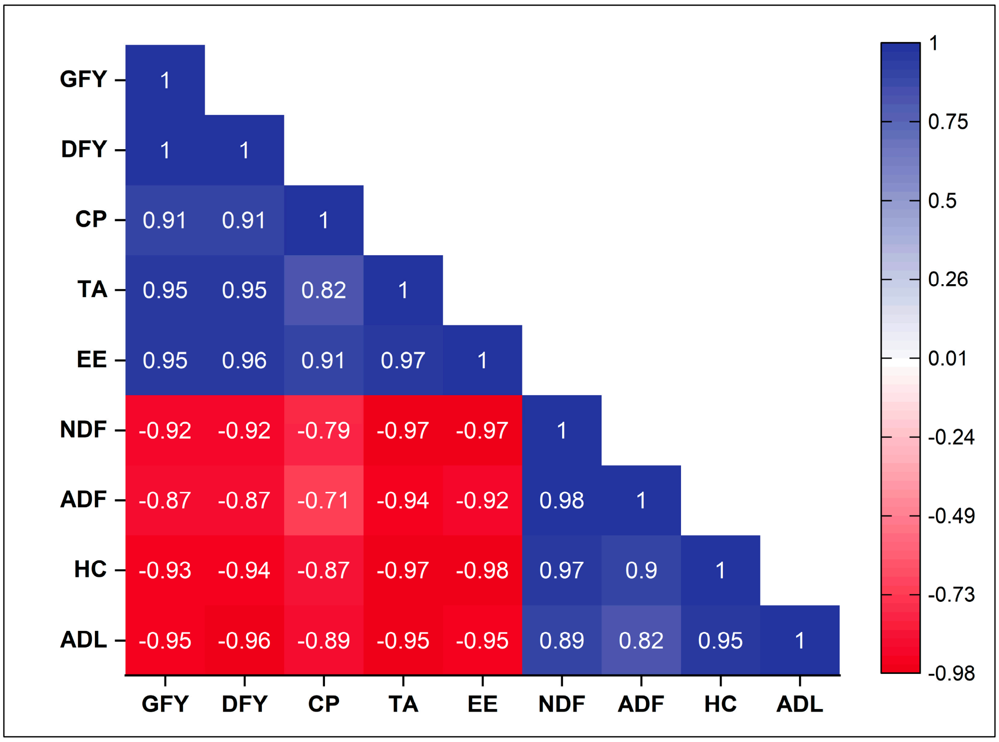


Figure 3. Pearson correlation coefficient heat map among green fodder yield, dry fodder yield, and quality traits as affected by the interaction among nitrogen and zinc managements. The correlation key and the scale read: red circle indicated negative correlation, blue circle indicated positive correlation, gray circle mean no correlation, smaller circle indicated lesser significance, and bigger circle indicated greater significance. The color intensity and size of the circle are relative to the correlation coefficients. Abbreviations: green fodder yield (GFY), dry fodder yield (DFY), crude protein (CP), total ash (TA), ether extract (EE), neutral detergent fiber (NDF), acid detergent fiber (ADF), hemicellulose (HC), acid detergent lignin (ADL).

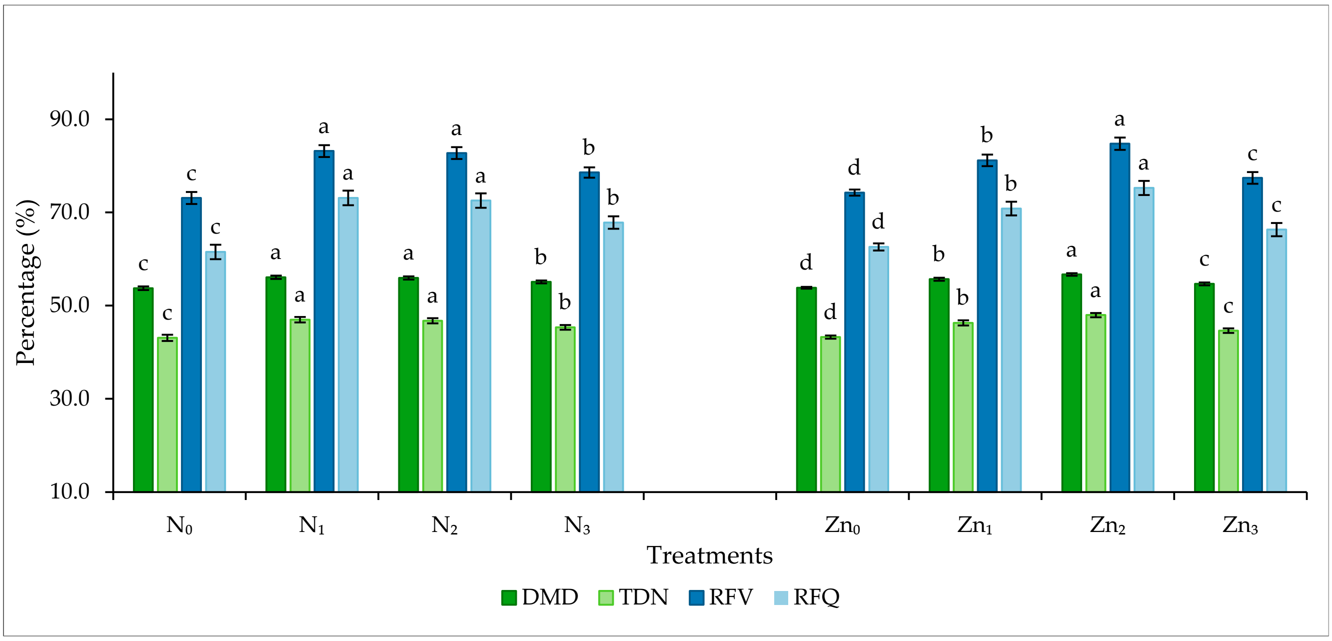


Figure 4. Dry matter digestibility (DMD), total digestible nutrients (TDN), relative feed value (RFV), and relative feed quality (RFQ) in the percentage of fodder maize as by nitrogen and zinc nano-fertilizers.

The same letters within each column indicate non-significant differences among the treatments using Tukey's HSD test ($p < 0.05$). Note: N_0: Control N, N_1: 100% RDN through urea, N_2: 50% RDN through urea + two sprays of nano-urea, N_3: 33.33% RDN through urea + two sprays of nano-urea, Zn_0: control Zn, Zn_1: soil application of $ZnSO_4$, Zn_2: foliar application of $ZnSO_4$ and Zn_3: foliar application of nano-Zn.

4. Discussions

4.1. Green and Dry Fodder Yield

Nitrogen is a critical nutrient for fodder maize and also a key determinant of fodder yield. Nitrogen is directly involved in photosynthesis as a constituent of chlorophyll pigment and other biological activities such as the absorption of water and minerals, vacuole storage, and xylem movement [28]. Thus, an efficient supply of nitrogen fertilizers to the growing crop is the most essential for their outstanding growth and yield [29]. Present study revealed that the 100% recommended dose of nitrogen through urea (N_1) and 50% RDN through urea + two sprays of nano-urea (N_2) were equally productive in terms of green and dry fodder yield. It is possible that the large surface area and small particle size of nano-urea (N_2) resulted in its great efficiency and assimilation inside the plant system, which lead to greater biomass production and in turn green fodder and dry fodder yield of fodder maize [30,31]. The nano-size of urea facilitates its penetrance into the plant from the leaf surface on which it is applied, as well as the uptake and nutrient use efficiency [32]. Also, nitrogen has a direct relationship with the amount of chlorophyll in a plant's tissue. Consequently, it leads to an increase in the number of photosynthates and protoplasmic components, along with an acceleration of cell division and elongation. This, in turn, leads to luxuriant vegetative growth of fodder maize in addition to a higher yield of green fodder [33–35].

Earlier studies have shown that Zn deficiency in soil is a well-documented problem worldwide. Zn is one of the leading factors of crop productivity reduction as it results in a significant penalty in plant performance, reported in several crops in countries such as India, China, Pakistan, and Australia [17,36]. Accordingly, zinc applications had significant positive effects on growth and development of plants leading to increased yield of maize [37]. The foliar application of $ZnSO_4$ @ 0.5% at six and ten leaves stages was found to be equally effective in terms of GFY and DFY as that of soil application of $ZnSO_4$ @10 kg ha^{-1}. This could be because of the amount of $ZnSO_4$ that was used as a basal dose in the soil at the time of sowing, which made early availability of Zn for various metabolic activities for better growth and yield. On the other hand, the positive and encouraging effects of $ZnSO_4$ fertilization on fodder yields of maize due to foliar application at six and ten leaves stages gave higher photosynthetic activities at later stages and enhances biomass production in plants [19]. In the present study, nano-zinc was not as effective as conventional $ZnSO_4$ fertilizer. The negative effects of metal nanoparticles on plants manifest themselves with several adverse effects on physiological management (for example, inhibition of root growth, delay of plant development) as well as on cell management (for example, disruption of chlorophyll synthesis, cell membrane damage or chromosomal aberration), as is reported from a study [38]. In this study, the effect of nutrient managements was quite similar in different years, suggesting a low influence of environmental factors such as rainfall and temperature.

The interaction effect of nitrogen and zinc was significant for GFY and DFY in fodder maize with the application of either 100% recommended dose of nitrogen or 50% RDN + 50% nano-urea along with the either foliar application of $ZnSO_4$ @ 0.5% six and ten leaves stages. A sufficient supply of zinc was found to be essential in assuring that the crop would effectively utilize the N fertilizer inputs. Zinc is a co-factor for several enzymes that are involved in the metabolism of carbohydrates, proteins, and auxins, as well as in the maintenance of membrane integrity [6,39,40].

4.2. Qualitative Traits

The concentration of fodder protein, soluble carbohydrates, and cell wall components is crucial from the digestion point of view by animals. These nutrients are provided to the rumen bacteria and influence the maintenance and production of animals [41,42]. Fertilization or nutrient management to fodder crop influences the protein and carbohydrate contents of fodder and its digestibility [43]. Further, NDF, ADF, hemicellulose, and ADL content provide details about the specific fiber fraction, their association, and digestibility of a fodder crop [44]. The whole fiber content is represented by neutral detergent fiber (NDF), whereas acid detergent fiber (ADF) represents the moderately indigestible portion of fodder plant [45]. Lignin becomes inaccessible to enzymatic degradation because strong bonds exist among lignin, polysaccharides, and cell wall protein [46,47]. This composition of fodder varies from crop to crop and agronomic interventions like nutrient management [34,48]. The availability of inorganic nitrogen (N) is essential for the synthesis of key plant components, including nucleic acids, chlorophyll, and proteins. The different quality characters of fodder maize i.e., crude protein (CP), ether extract (EE), and total ash (TA) were influenced significantly due to different N managements. Significantly superior quality fodder was obtained with both N_1 i.e., 100% RDN application through urea and N_2 i.e., 50% RDN through urea + two sprays of nano-urea. It might be due to adequate N fertilization that facilitates better metabolism to yield high amounts of protein in plant tissue. Nitrogen is directly involved in the amino acid composition of protein and thereby enhanced the nutritional quality of the fodder maize [34,49]. Nitrogen fertilization improved the EE content over control. This could be owing to the fact that fat production requires N [50]. Possible accumulation of other nutrients like P, K, Zn, etc. might contribute to the increase in ash content in fodder [4,51,52]. In contrast to this, N_1 and N_2 recorded the lower value of NDF, ADF, hemicellulose, and ADL compared to N_0 and N_3. The higher CP, EE, and total ash content under N_1 and N_2 added succulency to green fodder by reducing both the NDF, ADF, and ADL content [53]. It indicates efficiency of nano-urea applied with 50% of conventional urea as a result of a smaller size and a higher surface area [54,55] with enhanced cell content in fodder maize. This cell content resulted in thinner cell wall components [56].

Among the various Zn management, twice the foliar application of $ZnSO_4$ @ 0.5% (Zn_2) recorded CP, EE, and TA content on par with soil application of $ZnSO_4$ @ 10 kg ha^{-1} (Zn_1) and both were significantly higher than Zn_0 (control Zn) and Zn_3 (Foliar application of nano-Zn). This may be because the plants have an optimal amount of zinc, which is known to improve nitrogen uptake and, as a result, nitrogen plays an important part in the process of protein synthesis. Zinc is an essential component of ribosomes, which are required for plant development and protein production. Zinc enhances amino acid accumulation and thus protein production [57,58]. The synergistic effect of zinc on the availability of nitrogen further adds to the augmentation of these quality parameters [59], which may explain why there was a significant increase in total fatty acid content and ultimately the ether content in fodder maize [58]. Zn interacts positively with nitrogen and improves minerals like Cu, Mn, etc. absorption in plants [60], increasing total ash content in plants. This explains the increased total ash content with zinc application. The higher protein synthesis with foliar application of $ZnSO_4$ lowered the soluble carbohydrates [20,61,62]. This increased protein content could be responsible for the lower content of NDF and ADF in fodder maize. In our study, correlation of GFY, DFY, and qualitative traits i.e., CP, EE, and TA were positively correlated. Conversely, the value of NDF, ADF, HC, and ADL was negatively correlated with CP, EE, and TA content. In addition, the content of CP and EE was found to have a negative correlation with the various fiber fractions, such as NDF, ADF, hemicellulose, and ADL. The negative correlation of fiber with CP and EE was also reported by [63,64].

4.3. Nutritional Indices

Digestibility is an important aspect in the measurement of the nutritive value of animal feed/fodder. Dry matter intake (DMI) is an important parameter of fodder quality as it establishes the number of nutrients available to animals for health and production. In the present study, the DMI varies from 1.75% to 1.91% with various N managements and 1.78% to 1.93% among various Zn managements. N_1 and N_2 were statistically on par and had superior values of DMI, DMD, TDN, RFV, and RFQ over N_0 and N_3. Among Zn management, the application of Zn_2 was found to be significantly superior. The content of NDF is an indicator of DMI and is negatively correlated [3,25,47]. Dry matter digestibility (DMD) is the portion of the dry matter in a feed that is digested by animals at specified management of feed intake [25]. Total digestible nutrients (TDN) represent the energy content and digestibility of feed/fodder. Both DMD and TDN are negatively correlated with ADF content. Hence, a decrease in the ADF and NDF content led to higher DMI, DMD, and TDN values [7,10]. Relative feed value (RFV) is an index used to compare the quality of forages relative to their feed values. It is used to compare similar fodder for two important qualities, (i) how well it will be consumed and (ii) how well it will be digested. Relative forage quality (RFQ) denotes the fiber digestibility to estimate intake as well as the total digestible nutrients (energy) of the forage [58]. The higher nutritional indices with nitrogen and zinc management indicate quality fodder obtained with above nitrogen and zinc managements.

5. Conclusions

The experiment results suggested that applications of 50% recommended dose of nitrogen through urea and two foliar applications of nano-urea with two foliar sprays of $ZnSO_4$ @ 0.5% were found to be equally productive as the full recommended dose of nitrogen along with two foliar sprays of $ZnSO_4$ @ 0.5% in terms of herbage yield and quality of fodder maize. From this study, it can be reiterated that nano-urea can be an alternative to the conventional urea and both can be equally effective when applied with foliar spray of zinc sulfate.

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