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Effect of nano urea and nano zinc on crop productivity and nutrient dynamics in maize (*Zea mays* L.) under mid-hills of Himachal Pradesh

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Abstract

Maize (*Zea mays* L.) is an important cereal crop with high nutrient requirements, particularly nitrogen (N), phosphorus (P) and potassium (K). However, inefficient utilisation of N, can result in substantial nutrient losses and increased production costs. Nano-fertilisers such as nano urea and nano zinc have emerged as promising alternative to conventional fertilisers. The present experiment was laid out at Agricultural Farm of Shoolini University, Solan, Himachal Pradesh in randomised block design (RBD) comprising 9 nutrient management treatments, 3 replications and 1 variety. The experimental results exhibited maximum growth parameters, viz., plant height (228.5 cm) and dry matter accumulation (146.14 g plant^{-1}) in treatment (T_7) 100 % PK + 75 % N + 1 foliar spray (FS) (Nano urea + Nano zinc), which was statistically at par with (T_3) 100 % recommended dose of fertilisers (RDF) + 1 FS nano zinc 1.5 mL L^{-1}. The highest yield attributing characters viz., no. of cobs plant^{-1} and no. of grains cob^{-1} were recorded into treatment T_7 which were recorded statistically at par with T_3. Conjoint application of nano urea and nano zinc along with 25 % reduced conventional N was recorded highest grain, stover and biological yield which were increased to the tune of 32.8, 26.0 and 28.6 % over to (T_2) 100 % RDF (120 : 60 : 40 kg ha^{-1}) for grain, stover and biological yield, respectively. Total N, P and K uptake were also increased to the tune of 36.9, 41.9 and 31.1 % in treatment T_7 as compared to T_2. Among the treatments, (T_8) 100 % PK + 4 FS nano urea + 1 FS nano zinc fetched maximum cost of cultivation (₹42337 ha^{-1}) whereas, highest economic returns in terms of gross returns (₹134767 ha^{-1}), net returns (₹93414 ha^{-1}) and benefit–cost (B : C) ratio (2.26) were fetched in treatment (T_7) 100 % PK + 75 % N + 1 FS (Nano urea + nano zinc).

Keywords: economics; growth; maize; nano urea; nano zinc; nutrient uptake; yield

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1. Introduction

Maize (*Zea mays* L.) is the third most cultivated crop globally, followed by rice and wheat and it holds significant importance as a cereal crop worldwide (1). Maize is characterised by its tall stature, monoecious nature, bearing both male and female reproductive organs on the same plant. It is a cross-pollination and protandrous plant meaning the male flower matures before the female flower (2). Typically, maize grain contains 9–10 % protein, 70–80 % carbohydrates and 4–4.5 % fat (3). It's often called "Queen of Cereals" due to its unparalleled genetic yield potential among cultivated crops (4). Maize or corn is used for human consumption and animal feed. Besides this maize is also used as the raw material in the manufacturing of starch, oil, protein, alcoholic beverages, food sweeteners, pharmaceuticals, cosmetics, gums, etc. (5).

Nanoscience and nanotechnology are among the fastest growing fields in science and engineering and are leading to breakthroughs in energy, medicine, environmental science, biotechnology and other areas (6). Nano fertilisers offer a cutting-edge solution for improving crop nutrition and efficiency, ensuring better nutrient uptake, reduced losses and enhanced agricultural sustainability (7). The size of nano urea particle is about 30 nm (1 nm is one-billionth of a meter) and when compared to the conventional/ granular urea, it has about 10000 times more surface area to volume size. Nanotechnology enabled the design of ultra-small particles that gave higher surface-mass-ratios, which get absorbed by the plants when sprayed on their leaves (8). Indian Farmer Fertilizer Cooperative Limited (IFFCO), through its Nano Biotechnology Research Centre (NBRC) in Kalol, Gujarat, has pioneered advanced solutions locally, introducing innovative nano fertilisers such as nano urea, nano copper and nano zinc (Zn) (9). Among them, nano urea and nano zinc are particularly noteworthy. Nano urea, containing 4 % nitrogen (N) with particle sizes ranging from 20–50 nm, has a shelf life of

approximately 2 years and a zeta potential greater than 30. Made primarily from urea, it is enriched with essential nutrients and treated with non-ionic surfactants (10). To enhance stability, these nutrients are embedded in polymer matrices, forming nano clusters smaller than 100 nm. Its ultra-small particle size provides significantly larger surface area as compared to conventional urea, improving nutrient availability and efficiency (11). In fact, a single nanoparticle of urea is 55000 times smaller than conventional urea granule, allowing for superior absorption and utilisation by plants (12). Unlike conventional urea, which only allows 30–40 % of N utilisation while remaining 60–70 % quantity is losses in the form of leaching, denitrification and volatilisation which contribute in global warming (8).

A report of World Health Organization (WHO) indicates that the deficiencies in vitamin and mineral status, particularly of folate, iron, vitamin A and Zn, affect 50 % of all preschool aged children and 67 % of all women of reproductive age (WRA) worldwide (13). Human Zn deficiency was identified since 1961 (14). All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants (AICRP-MSPE) programme under the Indian Council of Agricultural Research (ICAR) analysed > 240000 soil samples from 2012 to 2018 from 28 states of India and reported approximately 38 % soil Zn deficiency in the Indian soils (15). Zinc is a crucial nutrient that plays a key role in boosting crop productivity, protein synthesis, chlorophyll production, gene expression, enzyme structure and energy production (16). Zinc is one of the most critical components for around 200 enzymes and transcription factors (17). Additionally, Zn positively influences crop yield through various processes, including auxin metabolism, the krebs cycle, pollen generation, resistance to pathogen infection and glucose metabolism. Fertilisation of nano Zn (< 100 nm particle size) is efficiently absorbed by roots as well as foliage parts and significantly enhance enzymatic activities in crop plants (18). Despite of that the increasing interest in nano-fertilisers, limited information is available on the combined foliar application of nano urea and nano Zn in maize under mid-hills conditions of Himachal Pradesh. Therefore, the present study was undertaken to evaluate the effects of nano urea and nano Zn fertilisation with conventional fertilisers, on growth, yield, nutrient uptake and economic feasibility of maize under mid-hill conditions of Himachal Pradesh.

2. Materials and Methods

The experiment was conducted during kharif season of 2024 at Agricultural farm, Kalaghat, Shoolini University, Solan Himachal Pradesh. Geographically, Kalaghat lies in the heart of Solan District of Himachal Pradesh at an elevation of 1270 m above mean sea level, latitude 30°51'26.9" N and longitude 77°09'29.6" E. During the experimentation maximum temperature (30.4 °C) being recorded during the month of July, while minimum temperature (10 °C) was during last week of October. The maximum relative humidity being (91 %) recorded during August and minimum relative humidity being (33 %) recorded during October, respectively while, total rainfall received during crop growing season was 545.1 mm. The soil of experimental field was sandy loam in texture, neutral in reaction, low in available Zn, medium in organic carbon and available N. While, high in available phosphorus (P) and potassium (K).

The experiment was laid out in randomised block design (RBD) with 3 replications and 1 variety i.e. Pratap Kanchan-2. Nine treatments were evaluated: control (T_1); 100 % recommended dose of fertilisers (RDF) (120 : 60 : 40 kg ha^{-1}) (T_2); 100 % RDF + 1 foliar spray (FS) of nano Zn at 1.5 mL L^{-1} (T_3); 100 % PK + 75 % nitrogen (N) + 1 FS of nano urea (T_4); 100 % PK + 4 FSs of nano urea (T_5); 100 % PK + 50 % N + 2 FSs of nano urea (T_6); 100 % PK + 75 % N + 1 FS of nano urea and nano Zn (T_7); 100 % PK + 4 FSs of nano urea + 1 FS of nano Zn (T_8); and 100 % PK + 50 % N + 2 FSs of nano urea + 1 FS of nano Zn (T_9). The sowing was done on 29th June 2024 at a spacing of 50 × 15 cm (Row × Plant) with using the seed rate 20 kg ha^{-1}. The gross plot size of experiment of each treatment was 5.0 × 4.0 m while the net plot size was 3.0 × 3.7 m. To eliminate the border effect, first and second row were discarded as border line effect and sampling row from both side of the plot and remaining central area was used as net plot to record the final yield and converted into q ha^{-1}.

The IFFCO nano urea (30 nm particle size) and nano Zn (12–15 nm particle size) were used in the experiment as a source of nano fertilisers which shows high surface area to volume size ratio and containing 4 % N and 1 % Zn, respectively. The nutrient management, entire quantity of P and K and 50 % N (treatment T_2 and T_3) was applied as a basal while the remaining N was applied as top dressing in to equal splits at knee high and tasselling stage. Treatments are getting 75 % N of RDF was applied 50 % as basal and remaining 25 % at knee high stage. However, treatments are getting 50 % N of RDF was applied total quantity as a basal. Treatments are getting the total quantity of N through nano-urea was applied at pre knee high, knee high, tasselling and grain filling stage, respectively at 20 days interval. Treatments are received 50 % N (Conventional urea) + 2 FS of nano-urea was done at knee high and tasselling stage. While treatment applied 75 % N (Conventional urea) + 1 FS nano-urea was done at tasselling stage. However, in treatments T_3 and T_7, FS of nano-Zn was done at knee high stage. Though, the treatments T_8 and T_9 are received nano Zn along with nano urea as tank mix at knee high stage of crop growth. The quantity of nano-urea and nano-Zn was used 2.0 mL and 1.5 mL L^{-1} water, respectively with 500 L ha^{-1} water was used for foliar spray at all the time. The foliar spray (FS) was done by using the knapsack sprayer with flat fan nozzle.

To eliminate weeds in all the plots of experimental area, atrazine at 1.0 kg a.i. ha^{-1} was applied as pre-emergence followed by one hand weeding (with the help of khurpi) was given at 25 days after sowing to minimising weed infestation. To control fall armyworm, coragen at

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0.5 mL L^{-1} water was applied at the time of infestation. The sources of nutrients were urea, single superphosphate and muriate of potash, respectively as per the treatment need (T_2). However, N management was different as compared to P and K and it was supplied irrespective of the treatment through, prill and nano urea. However, Zn was supplied through nano Zn as per the treatment. A total 3 irrigations were applied throughout the crop growing period when soil moisture was deficient.

Plant height of the five tagged plants in net plot was recorded from the base to tip of main shoot at harvest stage by using meter scale. The mean of five plants was expressed as the mean plant height in centimetres. Five tagged plants from net plot of each treatment were cut from the base of the plants. Plants were allowed to be sun-dried first and finally, oven-dried at 65 ± 5 °C for 72 hr up to dry till constant weight is obtained and recorded accordingly. The average dry matter accumulation was computed as g $plant^{-1}$.

The major yield-attributing characters were recorded during the experimentation and presented as the average number of each component. Five plants were randomly tagged in each plot and the number of cobs per plant was counted manually and computed as average number of cobs per plant. The total number of grains were obtained from five cobs of each plot and average number of grains per cob was manually counted for final observations. The weight of each individual cob was recorded by using a weighing balance after sun drying and the average weight was calculated and expressed in g cob^{-1}. The sun dried 100 grains were counted from the produce of each plot for recording seed index. After harvesting, each net plot biomass was weighed before threshing but after sun drying. The harvest index, is an index of source-sink relationship, was calculated as the ratio of economic yield and biological yield (19).

$$\text{Harvest index (\%)} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

Soil samples were collected from 0–15 cm depth from each plot and these samples were processed and analysed for various physico-chemical properties. The available N in soil was determined by alkaline potassium permanganate method (20). Available P was determined by ascorbic acid method (21). Available K in the soil was determined by extraction method (22). The processed plant samples were analysed by micro Kjeldahl method to determine N content. While, wet digestion (di-acid) method was used for preparation of aliquot to determine P and K content in plant. After estimation of NPK content per cent in grains and stover, the nutrient uptake was calculated by using the formula given below:

Nutrient uptake (kg ha^{-1}) = Nutrient content percent in grain × yield

Total uptake (kg ha^{-1}) = Uptake by grains + Uptake by stover

The protein content in grain was calculated by multiplying N content in grain by the factor, 6.25 (23) and expressed as protein content per cent.

Protein content (%) = 6.25 × N content (%) in grain

Protein yield was calculated by multiplying the protein content of each treatment with its respective grain yield and expressed in kg ha^{-1}.

Protein yield (kg ha^{-1}) = Grain yield × Protein content (%)

The cost of cultivation was calculated as:

Cost of cultivation (₹ ha^{-1}) = Common cost (₹ ha^{-1}) + Variable cost (₹ ha^{-1})

The gross returns were estimated by considering seed and stover yields for each treatment with the prevailing market price of the produce.

Gross returns (₹ ha^{-1}) = (Grain yield × Price) + (Stover yield × Price)

The net returns were worked out by using following formula:

Net returns (₹ ha^{-1}) = Gross returns - Cost of cultivation

The benefit-cost ratio was calculated by dividing net returns with the cost of cultivation for each treatment by using the formula given below:

$$\text{B : C ratio} = \frac{\text{Net returns}}{\text{Cost of cultivation}}$$

All the observations recorded during investigation were analysed by analysis of variance technique (ANOVA) using the statistical analysis (OPSTAT). The comparison of treatment means was made by the least significant difference at 5 % probability (p = 0.05).

3. Results and Discussion

Scheduling of N and zinc fertilisation significantly influenced the growth and yield-attributing traits of maize (Table 1). It is evident from the data that crop growth of maize in terms of plant height and dry matter accumulation was significantly affected by application of various treatments during the experimentation. Among the treatments, treatment T_7 produced the tallest plants (228.5 cm) and highest dry matter accumulation (146.14 g $plant^{-1}$) which was statistically at par with treatment T_3. While, shortest plant (130.1 cm) and lowest dry matter accumulation (52.37 g $plant^{-1}$) was recorded under T_1.

Yield attributing character is one of the most important parameters which can influence the yield and it is depend upon the crop management practices. The major yield attributing characters were recorded during the experiment which are number of cobs per plant, number of grains per cob and seed index. Among the treatments, application of T_4 was produced highest number of cobs per plant, number of grains per cob, seed index, cob weight, grain weight and shelling per cent

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which was statistically at par with treatment getting T_3. Although, T_1 without fertilisation of any nutrient was recorded minimum yield attributing characteristics.

Data embodied in Table 2 on yield and qualitative characteristics of maize had significant difference. Among the treatments, highest grain (53.41 q ha^{-1}), stover (79.65 q ha^{-1}) and biological yield (133.06 q ha^{-1}) of experimental crop was recorded under T_7 which was resulted statistically at par with treatment getting T_3 over rest of the treatments. The harvest index of experimental crop did not differ significantly by the conjoint application of conventional and nano fertilisers application and varied from 40.12–34.50 %. The highest and lowest value of harvest index was recorded into treatments T_7 and T_1, respectively. Though, the lowest grain, stover and biological yield were recorded under T_1.

Qualitative parameters viz, protein content and protein yield of maize was influenced by the treatments applied and significant improvement that was observed under, T_7 which was exhibited statistically at par with treatment is getting T_3 followed by other treatments. In contrast, the lowest protein content and yield was observed in T_1.

Optimising nutrient uptake to ensure balanced nutrient content in plant tissue is crucial for achieving maximum yield Tables 3 and 4. Among the treatments, treatment T_7 was resulted highest nutrient content per cent and uptake (N, P and K) which was exhibited statistically at par with treatment T_3. In contrast, the minimum nutrient uptake was observed in T_1, indicating the importance of both balanced nutrient application and the inclusion of micro-nutrient foliar sprays.

Data embodied in Table 5 on economic analysis of different treatments revealed significant differences in gross returns, net returns and benefit-cost ratio (B : C) ratio. Among the treatments, application of T_8, fetched maximum cost of cultivation (₹42337 ha^{-1}). However, highest gross returns (₹134767 ha^{-1}), net returns (₹93414 ha^{-1}) and B : C ratio (2.26) was recorded into treatment getting T_7. This economic advantage can be attributed to enhanced yield performance due to improved nutrient uptake and efficiency facilitated by conjoint use of nano urea and nano Zn and conventional fertilisers and enhanced B : C ratio demonstrating the cost-effectiveness of growing this crop. In contrast, T_1 exhibits the lowest economic returns in terms of gross returns (₹42981 ha^{-1}), net returns (₹12792 ha^{-1}) and B : C ratio (0.42).

Table 1. Effect of nano urea and nano zinc fertilisation on growth and yield attributing characteristics of maize

Treatments	Growth		Yield attributing characteristics		
	Plant height (cm)	Dry matter (g $plant^{-1}$)	No. of cobs per plant	No. of grains per cob	Seed index (g)
T_1	130.1	52.37	1.0	106.7	19.4
T_2	203.8	138.70	1.7	185.7	22.4
T_3	223.8	140.77	1.9	209.7	23.2
T_4	199.7	108.10	1.8	184.2	22.0
T_5	169.5	68.38	1.2	135.5	20.9
T_6	179.3	76.29	1.6	144.0	21.5
T_7	228.5	146.14	2.0	211.2	23.7
T_8	176.1	74.89	1.6	141.1	21.0
T_9	183.8	84.48	1.6	145.3	21.8
SEm±	5.6	2.92	0.09	1.07	0.42
LSD (p = 0.05)	16.1	8.50	0.26	3.1	1.22

Table 2. Yield and quality parameters of maize as influenced by application of nano urea and nano zinc

Treatments	Yield (q ha^{-1})				Quality parameters	
	Grain	Stover	Biological	Harvest index (%)	Protein content (%)	Protein yield (kg ha^{-1})
T_1	16.50	31.34	47.84	34.50	8.34	137.55
T_2	40.23	63.22	103.44	38.86	10.16	408.96
T_3	51.12	77.16	128.28	39.89	10.65	544.64
T_4	38.05	60.35	98.40	38.68	10.04	382.53
T_5	23.51	39.07	62.28	37.22	8.64	203.20
T_6	27.34	44.91	72.25	37.84	9.35	255.54
T_7	53.41	79.65	133.06	40.12	10.78	575.76
T_8	25.39	42.82	68.21	37.23	8.81	223.63
T_9	28.97	47.96	76.93	37.65	9.53	276.11
SEm±	1.35	1.84	2.54	0.86	0.09	15.80
LSD (p = 0.05)	3.93	5.35	7.38	NS	0.27	45.93

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Table 3. Effect of nano urea and nano zinc fertilisation on nutrient content per cent in grains and stover of maize

Treatments	Nutrient content (%)					
	Nitrogen		Phosphorus		Potassium	
	Grains	Stover	Grains	Stover	Grains	Stover
T_1	1.334	0.376	0.212	0.088	0.405	1.135
T_2	1.626	0.505	0.260	0.155	0.461	1.340
T_3	1.704	0.513	0.275	0.168	0.479	1.370
T_4	1.607	0.501	0.257	0.132	0.460	1.305
T_5	1.383	0.478	0.213	0.114	0.425	1.160
T_6	1.496	0.490	0.230	0.131	0.445	1.225
T_7	1.724	0.517	0.280	0.187	0.483	1.380
T_8	1.409	0.483	0.215	0.116	0.435	1.185
T_9	1.525	0.494	0.243	0.134	0.453	1.270
SEm±	0.01	0.01	0.01	0.01	0.01	0.01
LSD (*p* = *0.05*)	0.04	0.02	0.02	0.02	0.02	0.02

Table 4. Effect of nano urea and nano zinc fertilisation on nutrient uptake by maize

Treatments	Nutrient uptake (kg ha^{-1})								
	Nitrogen			Phosphorus			Potassium		
	Grains	Stover	Total	Grains	Stover	Total	Grains	Stover	Total
T_1	22.01	11.78	33.79	3.49	2.78	6.27	6.68	35.58	42.26
T_2	65.43	31.89	97.33	10.47	9.80	20.27	18.55	84.72	103.55
T_3	87.14	39.47	126.62	14.06	12.88	26.94	24.47	105.68	130.09
T_4	61.20	30.25	91.45	9.78	7.96	17.74	17.49	78.76	96.25
T_5	32.51	18.70	50.21	5.01	4.45	9.46	10.00	45.31	55.31
T_6	40.89	22.00	62.88	6.32	5.90	12.22	12.13	55.02	67.18
T_7	92.12	41.14	133.26	14.90	13.86	28.76	25.79	109.92	135.74
T_8	35.78	20.68	56.46	5.47	4.96	10.43	11.04	50.74	61.77
T_9	44.18	23.69	67.87	7.07	6.44	13.51	13.13	60.94	74.04
SEm±	2.53	0.74	2.72	0.38	0.98	0.62	0.68	2.42	2.54
LSD (*p* = 0.05)	7.35	2.15	7.89	1.09	2.85	1.81	1.97	7.03	7.39

Table 5. Effect of nano urea and nano zinc fertilisation on economics of maize

Treatments	Economics (₹ ha^{-1})			Benefit-cost ratio (B : C)
	Cost of cultivation	Gross returns	Net returns	
T_1	30189	42981	12792	0.42
T_2	41290	102148	60857	1.47
T_3	40702	129173	88471	2.17
T_4	41051	96725	55673	1.36
T_5	42098	60131	18034	0.43
T_6	41400	69813	28413	0.69
T_7	41354	134767	93414	2.26
T_8	42337	65056	22719	0.54
T_9	41639	74050	32411	0.78
SEm±	-	3163	3163	0.08
LSD (*p* = 0.05)	-	9195	9195	0.22

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4. Discussion

The application of nano urea and nano Zn as foliar spray, in addition to 25 % reduced N along with 100 % P and K through conventional fertilisers, played a pivotal role in improving vegetative growth of maize. The possible physiological mechanisms behind increase in plant height and dry matter accumulation observed in the present study may be associated with improved nutrient availability and utilisation under integrated conventional and nano-fertiliser management (24–26). The efficient usage and absorption of nitrogen are improved by application of nano urea in the form of FS (16, 26). Foliar application of nano urea can improve N availability may support chlorophyll formation, cell division and elongation and photosynthetic activity, thereby contributing to greater biomass production (16, 24–28). Zinc is one of the most important limiting micronutrients, which played a significant role in crop cycle and promote crop growth by the realising of an essential growth promoting hormone auxin which aids cell elongation and division by altering tryptophan metabolism, a precursor to indole-3-acetic acid (IAA). The IAA controls shoot apical dominance and total stem elongation. Zinc also aids in cytokinin production, which delays leaf senescence and promotes active vegetative growth these results are in line with the previous studies (16, 18, 28–30). Zinc is an essential micronutrient that plays an important role in plant growth, development and physiological processes. Adequate Zn fertilisation enhances maize growth and productivity by involving in several enzymatic and metabolic processes and by supporting photosynthetic activity and nutrient utilisation (18, 29). Zinc has also been associated with the regulation of plant growth through its involvement in auxin metabolism. Zinc may influence tryptophan metabolism, which is linked to the biosynthesis of IAA, an important auxin involved in cell division, cell elongation and shoot development (18). Consequently, adequate availability of Zn indicating the potential of nano Zn formulations to enhance vegetative growth and development of maize (18, 30).

The increment in yield contributing characters of maize might be due to conjoint application of nano urea and nano Zn with conventional fertilisers enhance nutrient acquisition and physiological activity. Nano urea acts as a catalyst to speed up enzymatic reactions and enhance nutrient absorption (9). As reported in earlier studies, Foliar feeding of N through nano urea and nano Zn improve in nutrient uptake which stimulate crop growth and yield component (10, 16, 28, 31, 32). Furthermore, previous researchers observed that, supply of nano urea and nano Zn might be maintaining hormonal balance such as auxin, cytokinin and gibberellins, enzymatic activity, photosynthesis, pollen formation, thereby involving in development of reproductive organs of the crop plants (29). Nano Zn also stimulates the biosynthesis of IAA, starting reproductive primordia and increasing the number of cobs per plant (29).

The increase in the grain and stover yield attributed due to enhanced yield attributes and vegetative growth. Nano urea and nano Zn activate key enzymes and are involved in auxin biosynthesis, promoting cell division, chlorophyll content and nutrient conversion, contributes to improved metabolic efficiency and enhancing assimilate translocation from source to sink and supporting both grains and stover production, leading to higher grain weight. The higher stover yield may be attributed to greater dry matter accumulation, which was associated with improved vegetative growth and morphological development, particularly increased plant height. The accelerated grain and stover yield contributed significantly to the overall enhancement of biological yield. The harvest index, representing the efficient translocation of food from source to sink, was favourably influenced by the foliar application of nano urea also indicates the photosynthetic accumulation in grain and not straw. The 25 % reduction in conventional N was effectively supplemented by nano urea, while the conjoint application of nano Zn with nano urea may have profound effect on nutrient-use efficiency, reduced N losses and thereby improved nutrient uptake and crop yield. Similar findings were supported by (10, 16, 25, 28, 33, 34, 35). Treatments are received entire quantity on N through nano urea was not outperformed might be due it can't fulfill the N requirement of crop and hence this shows the poor performance in growth and reproduction.

This enhancement can be attributed due to the synergistic effect of N and Zn which support accumulation of amino acids and protein synthesis. Nitrogen is a fundamental element in amino acid biosynthesis, serving as the building block of protein. In contrast, Zn is a key component in protein metabolism by stabilising chromatin structure, aiding DNA/RNA synthesis and supporting the function of RNA polymerase and ribosome biogenesis. Additionally, the presence of Zn enhances photosynthetic activity through NADPH/NADH formation, contributing to the synthesis of sugar and energy compounds necessary for protein production or key component ribosomal proteins and RNA polymerase, which is necessary for transcription and translation. It supports efficient protein assembly by preserving ribosomal structural integrity and functional effectiveness. Zinc and N work together to enhance protein content and yield. These observations are consistent with the findings of previous researchers (26, 32).

Nitrogen uptake significantly improved due to the synergistic effect of nano fertilisers with RDF enhancing the uptake of primary nutrients viz., N, P and K. These advanced formulations promote nutrient absorption, translocation and utilisation by improving root morphology, membrane permeability and metabolic functions. Previous studies demonstrated that foliar nutrition becomes particularly effective when root nutrient uptake is limited due to factors such as nutrient fixation, moisture deficiency and leaching losses (14). Moreover, nano urea reduces N losses (leaching and volatilisation), increasing nutrient use efficiency because of its FS and extremely small particle size, nano urea enables quick absorption and once entry into the plant system, get directly assimilated and stored in the leaves, then mobilised as needed through gradient diffusion and hormonal regulation. Zinc, particularly in its nano form, enhances N metabolism by activating key enzymes viz., alcoholic dehydrogenase, zinc dependent enzyme that

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catalyses the conversion of acetaldehyde to ethanol in root meristematic tissue, especially under anaerobic conditions. By sustaining anaerobic respiration, Zn ensures continuous energy supply in root tips, promoting active cell division and elongation. Thus, adequate Zn facilitates deeper and healthier root growth by maintaining enzyme functioning and energy metabolism under stress conditions. The nano Zn particles exhibit better penetration and mobility within the plant tissue supporting higher N uptake as also evidenced in previous studies by (28, 29, 33, 36, 37). Among the treatments, treatment T_8 incurred highest cost of cultivation due to additional expenditure on multiple foliar spray of nano fertilisers, the corresponding increase in yield and gross returns was insufficient in this treatment to compensate the additional cost and resulting comparatively low B : C ratio (0.54).

5. Conclusion

Based on the present findings, it can be concluded that application of T_7 (100 % PK + 75 % nitrogen (N) + 1 foliar spray (FS) (Nano urea + Nano zinc (Zn)), had resulted tallest plant, more dry matter accumulation, yield attributing characters, yield and quality of produce. Besides, this treatment also increases gross, net returns and B : C ratio in comparison to other treatments. However, minimum growth, yield attributes, yield, qualitative characters, gross, net returns and B : C ratio was reported under T_1 (Control). These findings are underscoring the economic viability of integrated use of nano urea and nano Zn with conventional fertilisers over reduced 25 % N requirement from recommended dose of conventional fertilisers. Therefore, the multi-season and multi-location studies involving different maize genotypes and environmental conditions are required to further validate the consistency and wider applicability of these findings.

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Authors' contributions

TS carried out the experiment, collected field data, performed statistical analyses and drafted the manuscript. RK contributed to experimental execution, data analysis and manuscript drafting and revision. SS contributed to data collection, literature review and manuscript editing. GM provided technical guidance, supervised the study and critically revised the manuscript. KC contributed to laboratory and analytical work and data preparation. ST contributed to field observations, data management and manuscript formatting. RS and AT contributed to data interpretation and manuscript revision. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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