



RESEARCH ARTICLE

Comparative analysis of foliar application of nano zinc with nano macro nutrients in spring maize in the Punjab Region

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Abstract

A field study was undertaken to assess the influence of foliar application of nano-zinc and nano-based macronutrients on the growth, physiological performance, nutrient uptake and overall productivity of spring maize. This field experiment was carried out during the spring season of 2025 at the agricultural farm of Lovely Professional University, Phagwara, under the prevailing agro-climatic conditions of Punjab. The experimental trial was arranged in a randomised block design (RBD) comprising 10 treatments that integrated the recommended dosage of fertilisers (RDF) with the foliar sprays of nano-zinc, nano-urea, nano-diammonium phosphate (DAP), and nano K_2O at 0.5 % and 1.0 % concentration at 35 days after sowing (DAS) and 55 DAS. Application of nano-zinc at 1.0% concentration along with 100 % RDF under treatment T3 at 35 and 55 DAS markedly improved plant height, number of functional leaves per plant, leaf area index, chlorophyll concentration, biomass accumulation and early flowering compared with RDF alone. The yield attributes, i.e., grain yield (52 q ha^{-1}), stover yield (71 q ha^{-1}) and harvest index (42.13 %), were also found to be highest under T3 (100 % RDF + foliar application of nano-zinc at 1.0 %). Its performance remained statistically at par with the treatment 100 % RDF + foliar application of nano-DAP at 1.0 % concentration under T7. In contrast, the control treatment (T0) recorded the lowest grain yield (21 q ha^{-1}), stover yield (37 q ha^{-1}) and harvest index (35.69 %) across growth, yield and nutrient parameters. The findings suggest that supplementing 100 % RDF + 1.0 % foliar spray of nano-zinc represents an effective and sustainable nutrient management strategy for improving physiological efficiency, nutrient acquisition and the overall productivity of spring maize under Punjab conditions.

Keywords: agronomic biofortification; foliar application; nano-fertiliser; nano-zinc; nutrient uptake; spring maize

Introduction

Maize (*Zea mays* L.), a member of the family Poaceae, is cultivated under diverse agro-climatic conditions for food, feed and industrial purposes. Due to its superior genetic yield potential, it has been recognised as the “Queen of Cereals”. According to FAO statistics for 2024 data, maize occupies approximately 209.95 million hectares globally, with the total grain output estimated at 1218.21 million tonnes and a mean productivity of 58.02 quintals per hectare. India has about 11.35 million hectares of maize, with a total production of 40.23 million tonnes. The total grain yield is 35.45 quintals per hectare; this is the cumulative effect of agronomic work, improved varietal work and climatic conditions in the area (1).

In Punjab, spring maize is cultivated over about 1.5 lakh hectares with a production of 14 lakh quintals and an average productivity of 93.9 q ha^{-1} (2). Nevertheless, the productivity of maize crops is often limited by micronutrient deficiencies, especially zinc (Zn), which is among the most common micronutrient disorders affecting maize growth and production under varying agro-climatic conditions (3). Zinc deficiency causes significant growth retardation, incomplete development of the plants, shortening of internodal distances and inadequate development of grain that results in massive loss of yield (4).

The traditional way to address these deficiencies is through conventional soil and foliar applications of micronutrient fertilisers. Nevertheless, these techniques are characterised by some limitations, such as nutrient leaching, fixation, surface runoff, volatilisation and low bioavailability in high pH and calcareous soils, which represent significant problems in the Punjab Region (5). Recent progress in nano technology has also introduced a new option: nano-fertilisers, nutrients contained in nanomaterials designed to release gradually and disperse throughout the soil (6). The growing research interest in nano-zinc and nano-macronutrient application in maize over recent years is illustrated in Fig. 1. Nano zinc oxide (ZnO) nanoparticles have shown high nutrient use efficiency and better uptake than traditional zinc sulphate formulations, owing to their higher surface area and improved bioavailability (7).

Nano-zinc combined with a nano-macro-nutrient formulation is a novel concept for comprehensive nutrient management in spring maize. Past research has shown that foliar application of various nano nutrients enhances nutrient absorption, increases photosynthetic productivity and results in higher grain yields than single-nutrient application (8). Moreover, studies have reported that foliar coating with nano-fertilisers results in a substantial decrease in nutrient requirements by nearly

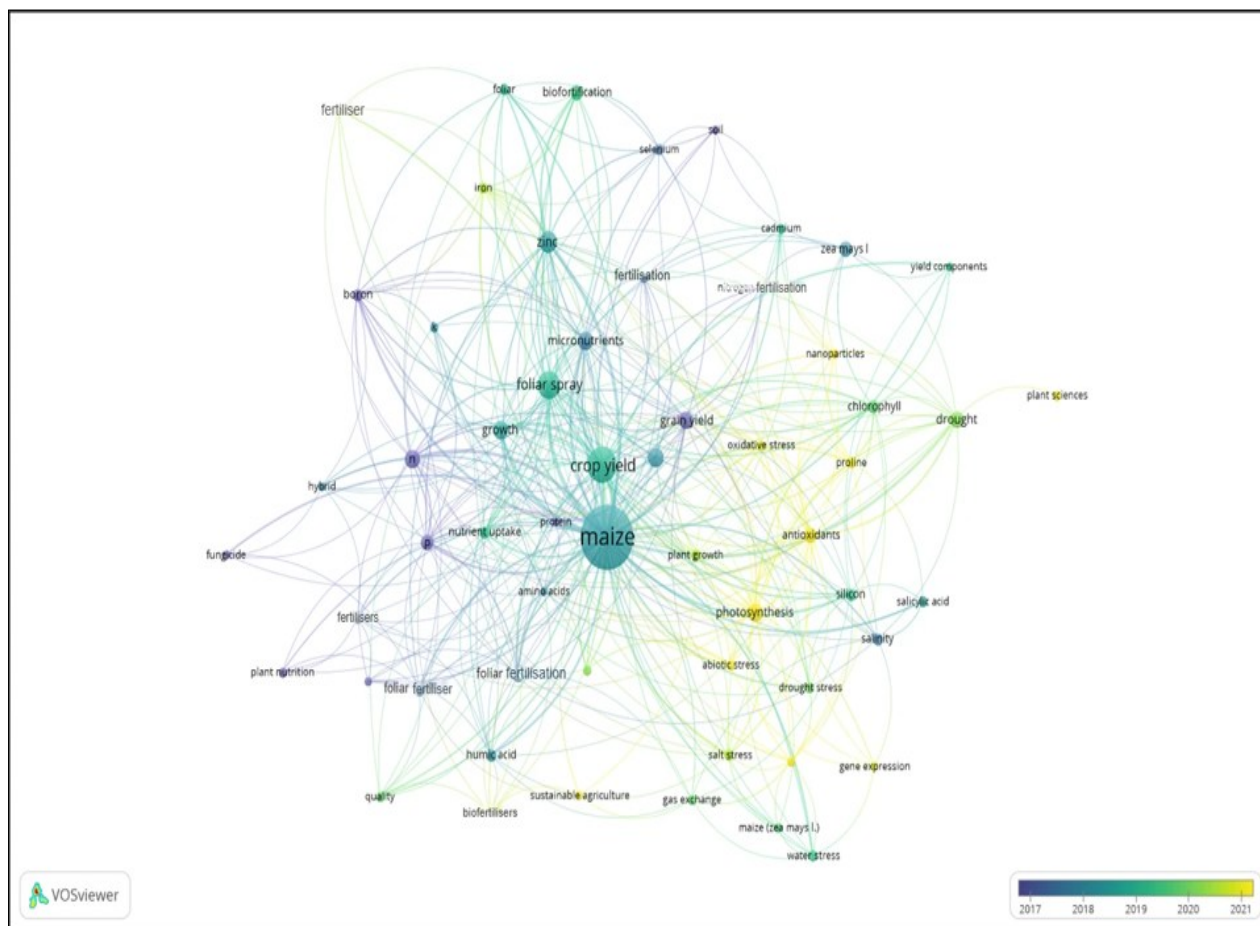


Fig. 1. Overlay visualisation illustrating the progression of research over time on the foliar use of nano zinc and macro nutrients in maize.

25 % relative to traditional fertilisers, without compromising or even deteriorating yields (9). Nano zinc oxide application enhanced the uptake of zinc in shoots and grains by up to 36.8 % and 33.3 %, respectively, compared with non-treated plants, as well as agronomic and nutrient use efficiencies (10).

Although the importance of nano-fertilisers is increasingly recognised, there is an essential research gap with respect to the relative effectiveness of nano-zinc on spring maize growth in the specific agro-climatic conditions of the Punjab Region, compared with its application in conjunction with nano-macronutrients [nitrogen (N), phosphorus (P) and potassium (K)]. The main aim of such comparative studies, as shown in Fig. 2, is the improvement of nutrient management systems, an increase in resource efficiency and strengthening sustainable agriculture (11). The current study was aimed at assessing the various impacts of the foliar application of nano-zinc and nano-macronutrients on the growth, yield, nutrient uptake and overall productivity of spring maize grown in Punjab.

The study is significant because it compares the foliar application of nano-zinc and nano-macronutrients in spring maize under the agro-climatic conditions of Punjab and evaluates their effects on growth, yield attributes, nutrient uptake, zinc enrichment and economics. The results provide baseline information on the relative performance of different nano-fertiliser treatments when applied with the recommended dose of fertilisers. Such evidence may help to identify more efficient nutrient management practices for spring maize and support future research use in crop production.

The findings are also relevant for assessing the potential of foliar nano-nutrition in maize improvement and agronomic biofortification.

Materials and Methods

Study area

The experimental study was conducted during the spring season of 2025 at the research farm of the Department of Agronomy, Lovely Professional University (LPU), located in Phagwara, Punjab, India. The site is located at 233 m above sea level and at 31.24° N latitude and 75.7° E longitude. The climate of the area is characterised by hot summers and mild winters, with an average annual precipitation of 600–700 mm, predominantly concentrated in the monsoon period. Physicochemical characteristics of the experimental site were assessed by collecting surface soil samples with a depth of 0–15 cm before sowing. The soil was also found to be sandy loam with an alkaline pH of 8.4. Early soil fertility tests showed that it had moderate amounts of organic carbon (0.52 %), available N (285 kg ha⁻¹), P (21.3 kg ha⁻¹) and P (278 kg ha⁻¹), implying moderately fertile soils where maize could grow.

Experimental design and treatments

The experiment was structured using a randomised block design (RBD) that included 10 separate treatment combinations and each treatment combination was repeated thrice, resulting in 30 experimental plots. Each plot measured 5 × 4 m, giving a total area of 20 m² per plot. The treatments included T0, which served as the control with no foliar application or fertiliser; T1, which used the recommended dosage of fertiliser (RDF); T2 consisted of RDF

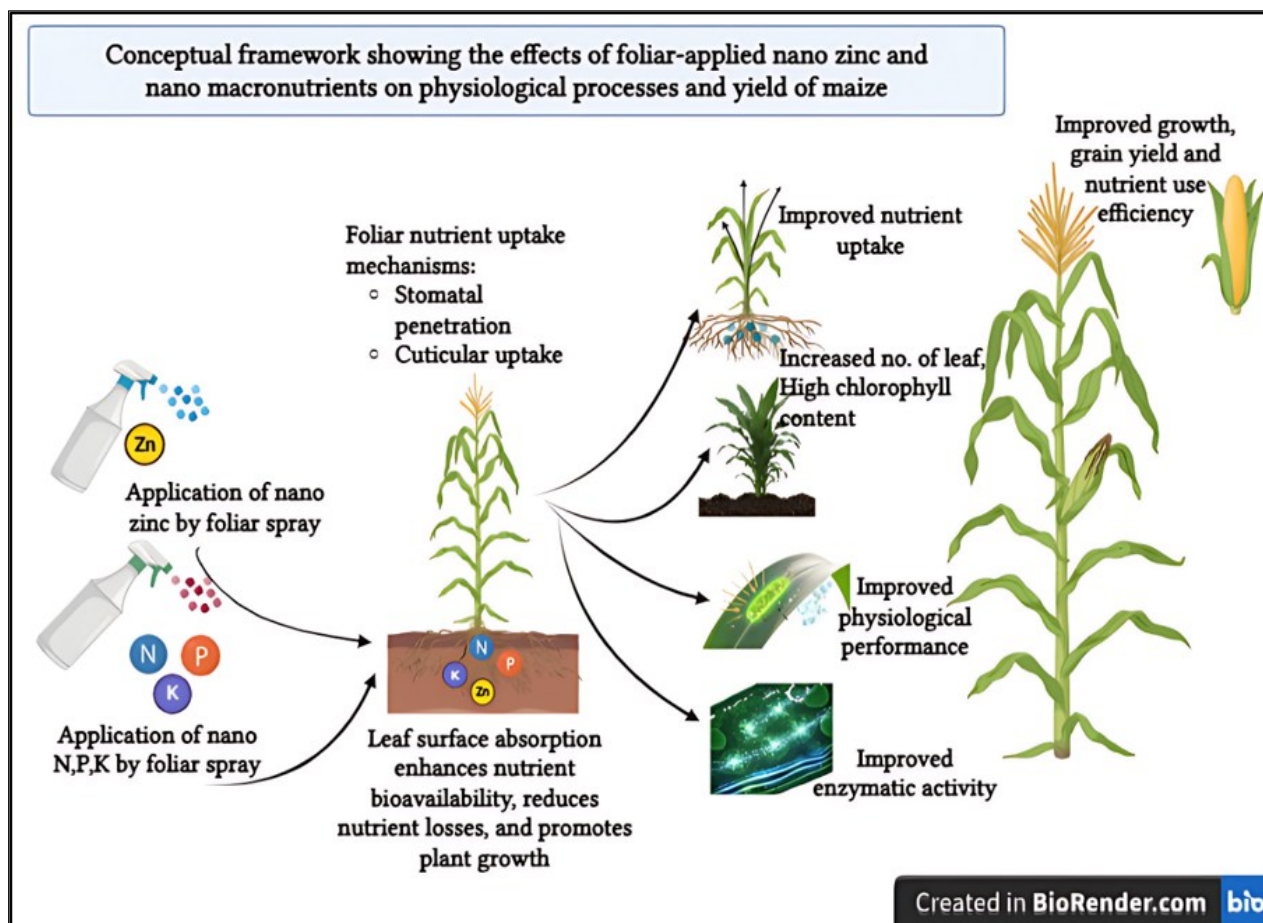


Fig. 2. Conceptual framework depicting the impact of foliar-applied nano-zinc and nano-macronutrients on maize's physiological processes and yield (11).

combined with the foliar application of nano-zinc at 0.5 % applied at 35 days after sowing (DAS) and 55 DAS, whereas T3 received RDF along with nano-zinc at 1.0 % at the same growth stages. T4 and T5 comprised RDF supplemented with nano-urea at 0.5 % and 1.0 %, respectively, sprayed at 35 and 55 DAS. Similarly, T6 and T7 included RDF integrated with nano-diammonium phosphate (DAP) at 0.5 % and 1.0 % foliar application at 35 and 55 DAS. In comparison, T8 and T9 involved RDF together with nano-K₂O at 0.5 % and 1.0 %, respectively, with foliar application carried out at 35 and 55 DAS.

Crop management

A high-yielding hybrid Spring Maize variety, Derby-1209, procured from a seed market of Punjab, was used for the experiment. The field was prepared by ploughing, harrowing and levelling to achieve a fine tilth. Maize (*Zea mays* L.) was sown manually by using the ridge and furrow method during the first fortnight of February, maintaining a row and plant spacing of 60 × 20 cm. A fertiliser schedule equivalent to 120 : 60 : 40 kg N : P₂O₅ : K₂O per hectare was supplied through urea, (DAP) and muriate of potash (MOP). The entire quantity of recommended P and K, along with one-third of the total N, was incorporated into the soil at the time of sowing. The remaining nitrogen was applied in two equal splits at the knee-height stage and tasselling stage of the crop. Using a knapsack sprayer, foliar sprays were performed twice: once at 35 DAS (vegetative stage) and once at 55 DAS (reproductive stage). The spray solution was uniformly applied at a spray volume of 500 L ha⁻¹ knapsack sprayer to ensure proper foliar coverage. Treatments included foliar sprays of nano zinc (0.5 % and 1.0 %), nano-urea (0.5 % and 1.0 %), nano-DAP (0.5 % and 1.0 %) and

nano-K₂O (0.5 % and 1.0 %) along with RDF and a control. The crop received a total of 6 irrigations at different growth stages through the ridge and furrow irrigation method. The pre-emergence herbicide atrazine (0.25 kg ha⁻¹) was sprayed on 3–5 DAS and then further hand weeding at 35 DAS and application of tembotrione 34.4 % SC at 0.5 mL L⁻¹ was given to control the weeds. To prevent the infestation of fall armyworm (*Spodoptera frugiperda*), Emamectin Benzoate was sprayed at 0.4 g L⁻¹ using 120 L of water per acre at 40 DAS. Harvesting was performed manually when the crop had attained physiological maturity and representative samples were taken to record growth attributes, yield attributes and the parameters of the nutrients according to the standard agronomic practices.

Observations recorded

Biometric factors were measured systematically to thoroughly evaluate the dynamics of spring maize growth, productivity and nutrients. A systematic recording of the necessary growth and yield parameters followed the significant phases of crop development. Observations were from 4 randomly selected plants in the inner rows of each plot. The plant height was measured from the soil surface to the apical meristem of the plant. The total number of functional leaves, leaf area index and the chlorophyll concentration on the leaf were also recorded in the field. A SPAD meter was used to measure the concentration of chlorophyll (mg m⁻²) in the leaves by measuring the photosynthetic efficiency of spring maize and the samples were representative green leaves to calculate the average leaf area per plant.

Yield parameters were assessed from the net plot area by taking an average of 4 randomly selected plants. The total grain

and stover yield, the total number of cobs per plant, cob length and its diameter and the total number of grains of each cob were determined. After identifying the yield of grain and stover, the values were put on a per-hectare basis. The harvest index was calculated to assess the efficiency of dry matter partitioning between economic yield and total biomass. In addition, the plant samples were analysed in the lab to estimate the total nutrient uptake by the plant. The nutrient use efficiency (NUE) indices were also calculated based on nutrient uptake and grain yield to provide a comprehensive assessment of treatment effectiveness and resource utilisation during the production of spring maize.

Nano-fertiliser characterisation and preparation for foliar application

The nano-fertilisers used in the present study, namely nano-urea, nano-DAP and nano-K₂O, were commercially procured from IFFCO (Indian Farmers Fertiliser Cooperative Limited) and nano-zinc (zinc oxide nano particles) was procured from Geolife Agri Tech in the form of stable aqueous colloidal suspensions. All the products conform to the standards prescribed under the Fertiliser Order, 1985, as amended by the Government of India's nano-fertiliser regulatory framework.

According to the manufacturer's specifications, the particle size ranged from 20–40 nm for nano-urea, 30–60 nm for nano-DAP, 25–55 nm for nano-K₂O and 25–50 nm for nano-zinc-the zeta potential of nano-zinc is between -18 and -22 mV, indicating satisfactory colloidal stability. Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) analyses confirmed a predominantly spherical morphology, with all formulations containing > 98 % active ingredients.

The concentrations of 0.5 % and 1.0 % were expressed on a weight/volume basis, representing 0.5 g and 1.0 g of nano-formulation per 100 mL of spray solution, respectively, as recommended by the manufacturer. Spray solutions were freshly prepared before each application by diluting the required quantity of stock formulation in water. No additional surfactants or dispersing agents were used, since the formulations were supplied as stable colloidal suspensions suitable for foliar application. The solutions were gently agitated for 5 min before loading into the knapsack sprayer to ensure uniform dispersion.

Statistical analysis

The significance of treatment effects on spring maize was determined by statistically analysing the experimental findings, which were recorded treatment-wise in three replicates. The means were used to represent the recorded observations that were tallied. The experimental data were subjected to statistical evaluation following the procedure appropriate for the randomised block design (12). Analysis of variance (ANOVA) was performed to test the significance of treatment effects and the computations were carried out using OPSTAT software to determine the overall differences among treatments. Treatment effects were tested for statistical significance using an *F*-test at a 0.05 probability level. In all cases where the *F*-test showed significant differences, critical differences (CD) were computed to compare the means of treatment. Standard error of mean (SE (m) ±) was also calculated to determine the difference between the replicates. Initial data processing and representations in graphs were done in Microsoft Excel 2021. The statistical methodology was used to guarantee that the experimental outcomes were well interpreted and comparisons between the nutrient management treatments were valid in spring maize.

Results and Discussion

Impact of foliar application of nano zinc and nano macronutrients on spring maize growth metrics

As shown in Table 1, applying nano zinc and nano macronutrients through foliar spray improved plant height, leaf area index (LAI), dry matter, chlorophyll content and crop phenology in spring maize, indicating better growth and physiological performance under balanced nutrient supply.

The improved response under nano-fertiliser treatments may be associated with smaller particle size, larger surface area and improved foliar absorption, which can enhance nutrient delivery and utilisation compared with conventional fertilisers.

Plant height (cm)

The data pertaining to the mean plant height of spring maize at 120 DAS are presented in Table 1 and graphically depicted in Fig. 3.

Table 1. Influence of foliar application of nano zinc and nano macro nutrients on the growth and physiological performance of spring maize

Symbol	Treatments	Plant height (cm)	No. of leaves	LAI	Dry matter accumulation (gm)	Chlorophyll content (mg m ⁻²)
T0	Control	135.59	5.3	0.7	86.5	31.07
T1	RDF	155.33	6.1	0.75	91.38	32.24
T2	RDF + Foliar spray of nano-zinc at 0.5 %	198.83	7.2	1.67	126.58	36.23
T3	RDF + Foliar spray of nano-zinc at 1.0 %	220.38	8.1	1.93	148.86	38.47
T4	RDF + Foliar spray of nano-urea at 0.5 %	185.43	6.4	1.28	121.76	34.87
T5	RDF + Foliar spray of nano-urea at 1.0 %	178.52	6.3	1.09	118.14	37.3
T6	RDF + Foliar spray of nano-DAP at 0.5 %	201.53	7.6	1.69	128.92	37.69
T7	RDF + Foliar spray of nano-DAP at 1.0 %	212.23	7.8	1.81	133.35	37.73
T8	RDF + Foliar spray of nano-K ₂ O at 0.5 %	174.38	5.8	0.84	106.46	33.2
T9	RDF + Foliar spray of nano-K ₂ O at 1.0 %	195.62	6.9	1.42	123.35	35.53
SE(m)±		0.159	0.05	0.005	0.086	0.034
C.D. (<i>p</i> ≤ 0.05)		0.477	0.151	0.016	0.256	0.101

RDF: recommended dose of fertilisers; LAI: leaf area index; DAP: diammonium phosphate; K₂O: potassium oxide;

SE (m)±: standard error of mean; CD (*p* ≤ 0.05): critical difference at the 5 % level of significance.

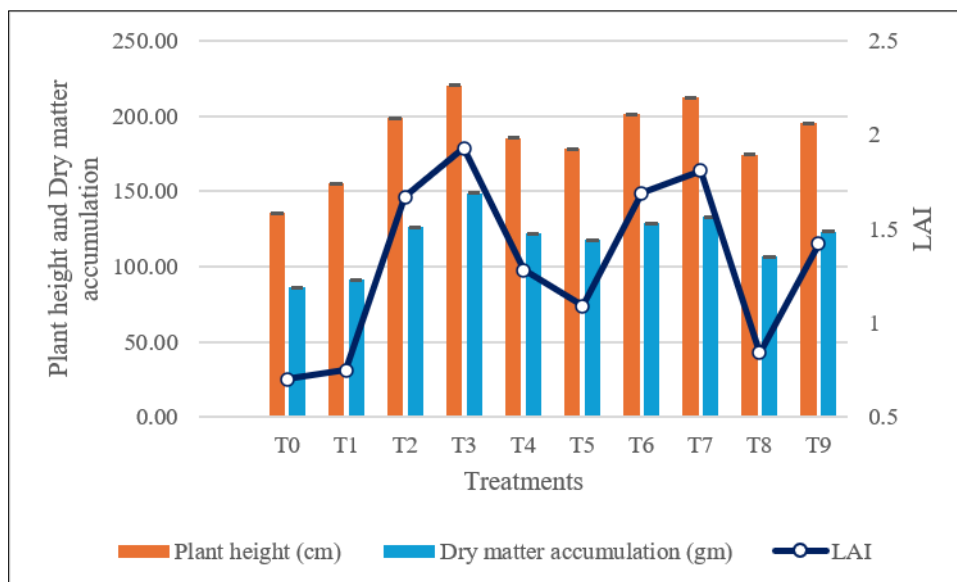


Fig. 3. The growth patterns of spring maize as affected by the foliar application of nano zinc and nano macronutrients, showing differences in plant height, biomass growth and leaf area index (LAI).

Treatment T3 (RDF + Foliar nano-zinc spray at 1.0 %) recorded the significantly highest plant height of 220.38 cm, which was statistically at par with T7 (RDF + Foliar nano-DAP spray at 1.0 %) recording 212.23 cm. In contrast, the minimum plant height was recorded in control T0 (135.59 cm).

The significantly greater plant height under T3 could be linked to adequate zinc supply through nano-zinc at 1.0 %, which improved nutrient use efficiency and supported vigorous vegetative growth. The superior performance of T3 over T1 (RDF alone) suggests that improvement is not merely due to supplemental nutrition but also related to enhanced bioavailability and efficient nutrient delivery through nano-formulations. The statistically comparable performance of T7 suggests that nano-DAP also supported plant height through improved N and P availability. The lowest height in control T0 confirms that inadequate nutrient supply limits vegetative growth in maize. These findings align with previous reports suggesting that foliar application of zinc, along with recommended fertilisation, significantly increased plant height in maize (13).

Number of functional leaves

The effect of different nutrient management practices on the leaf development of spring maize has been presented in Table 1 and graphically illustrated in Fig. 4. Treatment T3, receiving the recommended fertiliser dose along with a 1.0 % nano-zinc foliar application at 35 and 55 DAS, produced the greatest leaf count of spring maize (8.1). This was statistically comparable with treatment T7 (RDF + Foliar nano-DAP spray at 1.0 % at 35 and 55 DAS), recording 7.8 functional leaves. The control treatment produced the fewest functional leaves (5.3).

T3 produced a significantly higher number of functional leaves, which may be attributed to improved nutrient availability under nano-zinc application and supported better leaf development at harvest. T7 also remained statistically at par, indicating improved leaf development under nano-DAP application. The lowest leaf count in control T0 clearly reflects the consequence of complete nutrient deprivation on leaf development in spring maize. These results are consistent with previous studies which reported that foliar supplementation of nano-zinc and nano-DAP improved leaf production and canopy

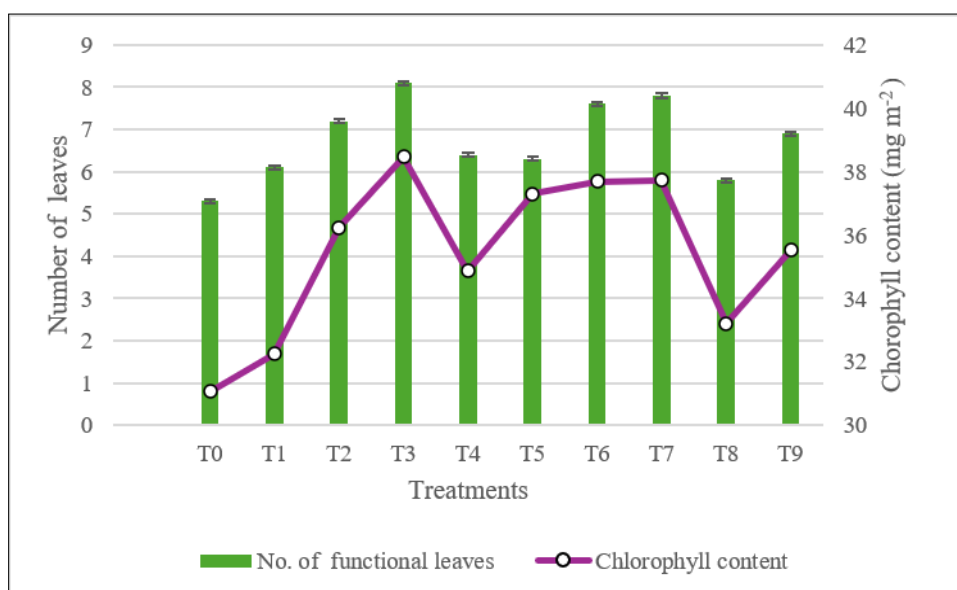


Fig. 4. The regulatory impact of foliar-applied nano zinc and nano macronutrients on leaf development and chlorophyll levels in springmaize.

development through better nutrient utilisation and translocation within the plant (14, 15).

Leaf area index

As presented in Table 1 and graphically illustrated in Fig. 3, nano-fertiliser treatments improved the leaf area index (LAI) of spring maize. Treatment T3 (RDF+ foliar nano-zinc spray at 1.0 %) emerged as the best performer with a significantly higher LAI of 1.93, remaining statistically comparable with T7, which recorded an LAI of 1.81. The lowest leaf area index (0.70) was the control treatment (T0).

Adequate zinc supply through nano-zinc at 1.0 % in T3 likely supported the better canopy development and leaf area expansion. T7 remained statistically comparable with T3, suggesting that nano-DAP effectively supported canopy development in spring maize. The drastically reduced LAI in control T0 highlights that nutrient-deprived conditions severely restrict canopy development in maize. These findings are consistent with previous studies reporting that foliar zinc application improved leaf area and canopy development in maize (10, 16).

Dry matter accumulation (g)

Dry matter accumulation is a crucial measure of crop growth, as it reflects the cumulative outcome of plant growth and biomass production during crop development. As shown in Table 1 and illustrated in Fig. 3, the treatment T3 (RDF + foliar spray of nano-zinc at 1.0 %) registered the highest dry matter accumulation (148.86 g plant⁻¹). In contrast, T7 (RDF + foliar nano-DAP spray at 1.0 %) with 133.35 g plant⁻¹ remained statistically comparable. On the contrary, the control treatment (T0) recorded the lowest dry matter accumulation (86.50 g plant⁻¹).

Enhanced nutrient availability under T3 likely contributed to greater biomass accumulation. The performance of T7 indicates improved biomass accumulation under nano-DAP application. The poorest biomass recorded in T0 underscores the indispensable role of external nutrient management in achieving dry matter production. These results align with the previous

studies, reporting improved biomass production under zinc fertilisation in maize (17).

Chlorophyll content (mg m⁻²)

Chlorophyll content measured as SPAD value ranged from 31.07 to 38.47. As shown in Table 1 and in Fig. 4, the highest chlorophyll content (38.47) was recorded under T3 (RDF +1.0 % foliar application of nano-zinc), which remained statistically at par with T7 (RDF + 1.0 % foliar application of nano-DAP) (37.73).

The higher SPAD values under zinc treatments may indicate improved chlorophyll synthesis, which may be associated with improved nutrient metabolism under adequate micronutrient availability. Similarly, the application of nano-DAP also supported chlorophyll retention through adequate N supply under T7, which is a direct component of the chlorophyll molecule. The control treatment (T0) recorded the lowest chlorophyll content (31.07), indicating the adverse effect of nutrient deficiency on chlorophyll formation. This has been previously reported by other studies, which showed that zinc fertilisation enhances chlorophyll concentration and photosynthetic activity in maize (18, 19).

Days to 50 % tasselling and silking

Different nutrient treatments notably affected crop phenology, with the time to reach 50 % tasselling ranging from 57–75 days and 50 % silking from 61 to 79 days. The earliest occurrences of tasselling and silking were noted in T3 (RDF + foliar spray of nano-zinc at 1.0) at 57 and 61 days, respectively, which were statistically comparable with T7 (RDF + foliar spray of nano-DAP at 1.0), recording tasselling and silking at 61 and 65 days, respectively. The control treatment T0 recorded maximum days to tasselling of 75 days and silking of 79 days.

The earliest tasselling and silking under T3 can be explained by adequate zinc availability through nano-zinc at 1.0 %, which supported the timely transition from vegetative to reproductive stage compared to conventional fertilisation. The performance of T7 was found to be statistically comparable, indicating that nano-DAP also effectively supported timely crop

Table 2. Impact of foliar nutrition with nano zinc and nano macro nutrients on the yield attributes of spring maize

Symbol	Treatments	No. of cobs plant ⁻¹	Length of cob (cm)	Diameter of cob (cm)	Number of grains cob ⁻¹	Test weight (g)	Grain yield (q ha ⁻¹)	Stover yield (q ha ⁻¹)	Harvest index (%)
T0	Control	1.7	12.73	3.1	268.83	21.33	21	37	35.69
T1	RDF	1.85	15	3.42	348.7	24.63	28	42	39.83
T2	RDF + Foliar spray of nano-zinc at 0.5 %	2.08	19.1	3.71	452.04	28.93	35	51	40.94
T3	RDF + Foliar spray of nano-zinc at 1.0 %	2.3	23.37	4.18	620.62	37.13	52	71	42.13
T4	RDF + Foliar spray of nano-urea at 0.5 %	1.98	17.8	3.88	416.04	30.27	30	48	38.33
T5	RDF + Foliar spray of nano-urea at 1.0 %	1.94	17.03	3.55	353.1	28.50	29	46	38.33
T6	RDF + Foliar spray of nano-DAP at 0.5 %	2.14	20.4	3.98	420.7	32.40	40	58	40.75
T7	RDF + Foliar spray of nano-DAP at 1.0 %	2.24	21.86	4.07	475.53	34.30	48	67	41.77
T8	RDF + Foliar spray of nano-K ₂ O at 0.5 %	1.92	15.83	3.66	398.76	27.47	27	45	37.29
T9	RDF + Foliar spray of nano-K ₂ O at 1.0 %	2.04	19.36	3.95	334.8	31.37	31	51	37.73
SE(m)±		0.005	0.103	0.112	7.379	0.981	2.07	3.219	2.392
C.D. (<i>p</i> ≤ 0.05)		0.002	0.034	0.037	2.464	0.328	0.691	1.075	0.799

DAP: diammonium phosphate; RDF: recommended dose of fertiliser.

phenological development in maize. The significantly delayed tasselling and silking in control T0 confirms that inadequate nutrient supply slows down crop phenological development under field conditions. These findings agree with previous studies, which showed that a sufficient and balanced supply of nutrients enhances physiological and metabolic processes, thereby reducing the time to tasselling and silking (20–22).

Impact of foliar application of nano zinc and nano macronutrients on the yield attributes of spring maize

As presented in Table 2, yield and yield attributes of spring maize varied significantly among treatments. These variations may be associated with the application of different nano-nutrient sources through foliar treatments as part of nutrient management. Nano-fertilisers may have enhanced crop performance through smaller particle size, controlled nutrient release and improved leaf penetration efficacy.

Number of cobs per plant

The different nutrient management strategies significantly influenced the total number of cobs per plant, as evident from Table 2 and Fig. 5. T3 (RDF + foliar spray of nano-zinc at 1.0 %) produced the maximum number of cobs per plant (2.30). It remained statistically at par with T7 (RDF + foliar spray of nano-DAP at 1.0 %) (2.24). This response may be associated with better nutrient supply during critical growth stages, which supported crop growth and cob formation. Control treatment exhibited the lowest count of cobs per plant (1.70), indicating the limited cob initiation under nutrient-deficient conditions. These findings agree with previous reports (23, 24), which showed that balanced zinc and P nutrition can improve reproductive performance in maize.

Length of cobs per plant (cm)

The application of a foliar spray containing nano zinc and nano macronutrients significantly influenced cob length, as shown in Table 2. Fig. 5 shows that treatment T3 (RDF + 1.0 % foliar spray of nano-zinc) registered the maximum cob length (23.37 cm) among all the treatments. It remained statistically at par with T7 (RDF + foliar spray of nano-DAP at 1.0 %), having 21.86 cm cob length.

Zinc supports enzyme functions and growth regulation, which may contribute to better cob development and greater cob length in maize. On the other hand, treatment T7 may have promoted cob growth because of sufficient phosphorus levels. The shortest cob length (12.73 cm) was recorded in the control (T0), which indicated a poor development of the cob in the conditions of nutrient limitation.

The results are consistent with previous studies (24, 25), which have reported the beneficial impact of balanced zinc and phosphorus nutrition on the growth of the cob in maize.

Diameter of cob per plant (cm)

Cob diameter responded significantly to nutrient management practices. As presented in Table 2 and illustrated in Fig. 5, RDF with foliar application of nano-zinc at 1.0 % under T3 gave the highest cob diameter (4.18 cm). This remained statistically at par with T7 (RDF + foliar application of nano-DAP at 1.0 %), which had a cob diameter of 4.07 cm. Foliar application of nano-zinc may have supported better cob diameter during reproductive development. Nano-DAP may have contributed to greater cob diameter through adequate P supply during ear development. Conversely, the minimum cob diameter (3.10 cm) was observed in the control treatment, indicating limited cob growth under nutrient-deficient conditions. The current evidence supports the previous studies, which supported that balanced zinc and phosphorus nutrition improved cob diameter in maize under better nutrient management conditions (19, 26, 27).

Number of grains per cob

Different nutrient management treatments significantly affected the number of grains per cob. The highest grain count per cob (620.62) was recorded under treatment T3 (RDF + foliar spray of nano-zinc at 1.0 %), as presented in Table 2 and illustrated in Fig. 6, indicating that adequate zinc availability likely supported better grain set and kernel development in spring maize. T7 (RDF + foliar spray of nano-DAP at 1.0 %) remained statistically comparable with T3, with a reading of 475.53 grains per cob, indicating that phosphorus availability may also have supported kernel development. The control treatment recorded the lowest number

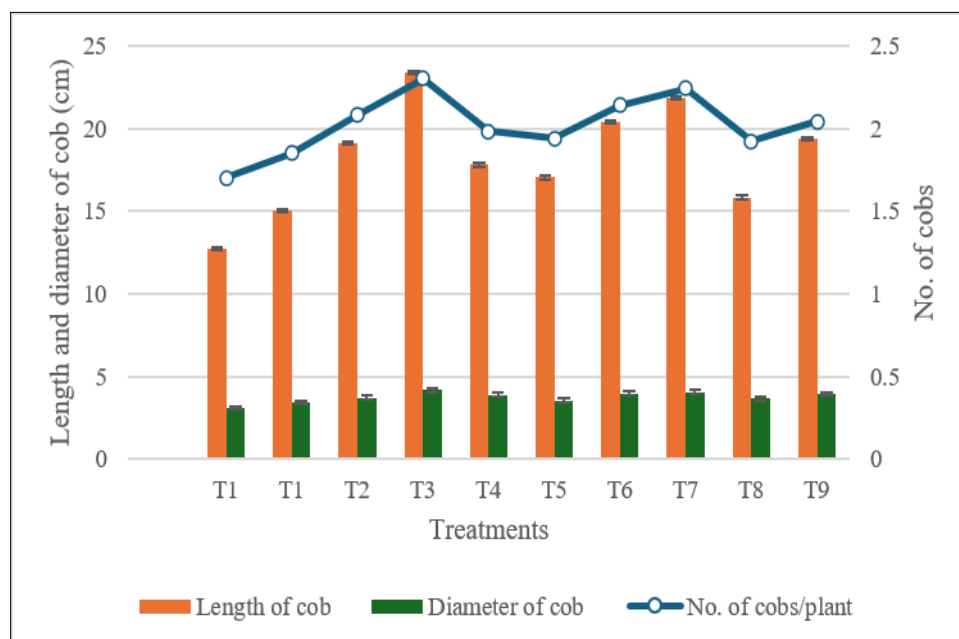


Fig. 5. Changes in the reproductive structure of spring maize with nano nutrient foliar treatments, highlighting the number of cobs per plant and cob length parameters.

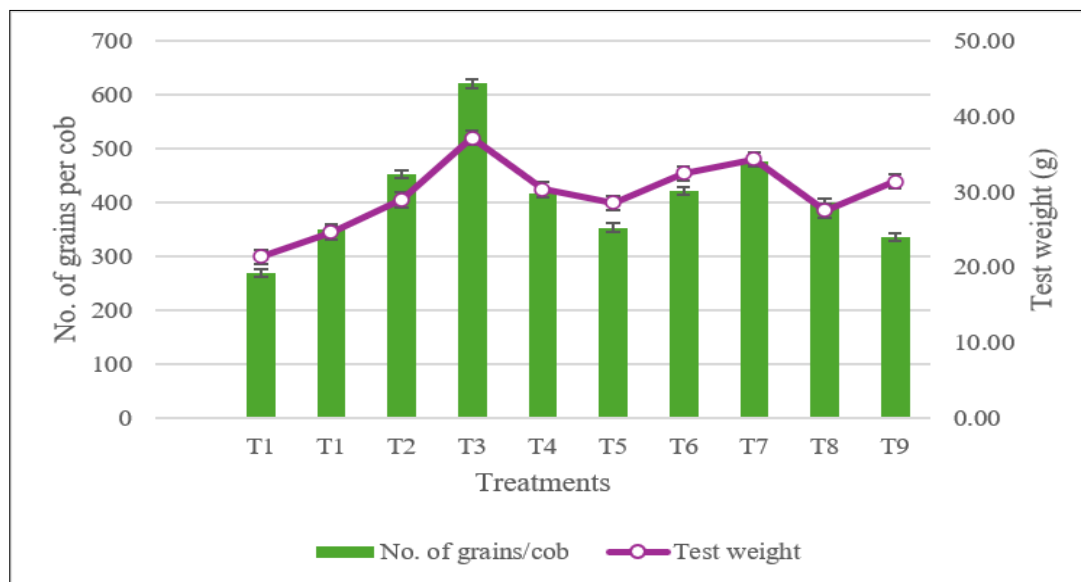


Fig. 6. The effect of nano zinc and nano macronutrient sprays on grain development traits, such as the number of grains per cob and the weight of 100 seeds, test weight in spring maize.

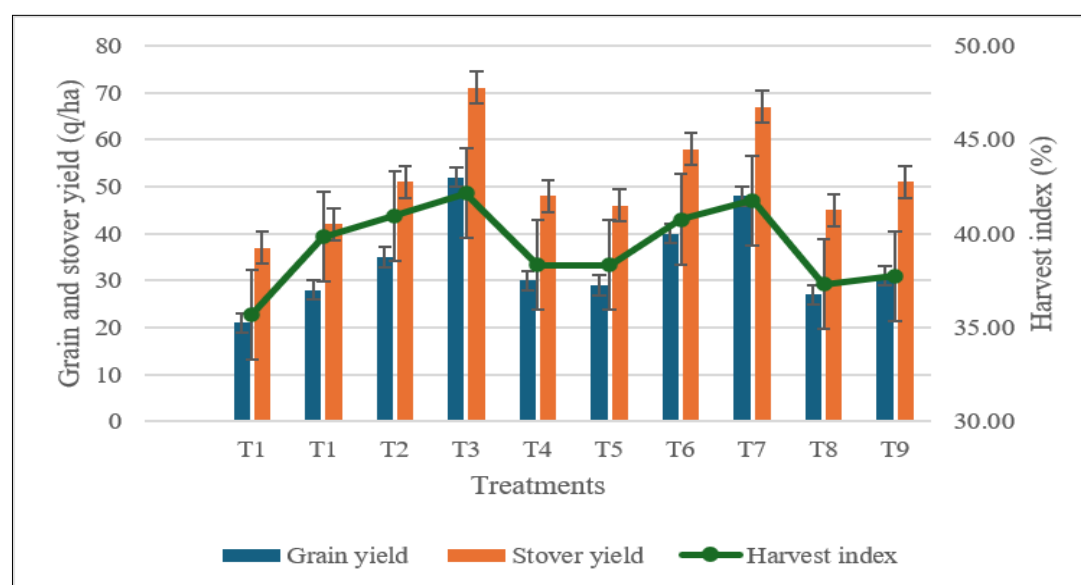


Fig. 7. Overall response of yield-related characteristics of spring maize to the foliar application of nano zinc and nano macronutrients.

of grains per cob (268.83), indicating poor grain set in nutrient-deficient conditions. Previous reports (20, 24) have also shown similar responses, where balanced zinc and P application increased the number of kernels in maize.

Grain yield (q ha^{-1})

The grain yield of spring maize was significantly affected by different nutrient management practices in Fig. 7 and in Table 2. The peak grain yield (52 q ha^{-1}) was achieved under T3 (RDF + foliar spray of nano-zinc at 1.0 %), which is an increase of 147.6 % above the control and it suggests that zinc likely promoted kernel development and assimilate translocation. The T7 (RDF + foliar spray of nano-DAP at 1.0 %) treatment resulted in 48 q ha^{-1} , which increased by 128.6 % relative to the control and was also found to be statistically comparable in T3, which showed the complementary nature of phosphorus in enhancing grain yield. On the contrary, the poorest crop productivity noted was 21 q ha^{-1} , the lowest grain yield recorded under the control treatment, because of low nutrient availability. Similar yield increases have been reported previously (23, 28) under balanced nutrition of zinc and phosphorus.

Stover yield (q ha^{-1})

Marked variation in stover yield was observed in Table 2 and Fig. 7 due to the different nutrient management practices applied to spring maize. Maximum stover yield was observed in T3 (RDF + foliar spray of nano-zinc at 1.0 %) and this represented a 91.9 % increase over the control, which demonstrates the effect of zinc on increasing vegetative growth, biomass accumulation and photosynthetic efficiency. The T7 (RDF + foliar spray of nano-DAP at 1.0 % treatment yielded 67 q ha^{-1} , which is statistically at par with treatment T3, meaning the positive effect of P on dry matter production. In contrast, the control plot recorded the minimum stover yield (37 q ha^{-1}), indicating that biomass production was poor in nutrient-deficient conditions. These findings are consistent with previous researchers (29, 30) claiming that the balanced use of zinc and P has a significant effect on stover production in maize.

Test weight (g)

Nutrient management treatments had a significant effect on test weight (100-seed weight), which is a considerable parameter that determines seed quality and grain filling. As presented in Table 2 and Fig. 6, the maximum test weight was obtained in T3 (RDF + foliar

spray of nano-zinc at 1.0 %) with 37.13 g, which remained statistically at par with T7 (RDF + foliar spray of nano-DAP at 1.0 %), recording 34.30 g. Improved nutrient supply facilitated grain filling in spring maize. Although T3 and T7 were statistically comparable, the slightly higher value in T3 suggests a possible role of zinc in grain development. The control treatment recorded the lowest index of seed development (21.33 g), indicating poor seed development due to nutrient deficiency. The increase in test weight observed in the present study agrees with previous reports (31, 32).

Harvest index (%)

The harvest index, a crucial measure of biomass partitioning efficiency, was significantly affected by the nutrient management treatments. As shown in Table 2 and Fig. 7, the treatment that achieved the highest harvest index was T3 (RDF + foliar spray of nano-zinc at 1.0 %), with a value of 42.13 %, which was statistically at par with treatment T7 (RDF + foliar spray of nano-DAP at 1.0 %) with a value of 41.77 %. Zinc is known to support enzyme activity and plant growth, which may contribute to better dry matter accumulation and grain development. In contrast, nano-DAP contributed to grain development through P availability during reproductive stages. On the other hand, the control treatment exhibited the lowest harvest index (35.69 %), reflecting poor assimilate partitioning under nutrient-deficient conditions. The variations in the harvest index observed in this study align with previous findings (23, 24).

Nitrogen, phosphorus and potassium uptake and zinc enrichment in spring maize

N, P, K uptake (kg ha^{-1})

The uptake of essential primary nutrients by grain and stover differed significantly under various treatment combinations, as shown in Fig. 8. Nutrient uptake was the greatest for T3 (RDF + foliar spray of nano zinc at 1.0 %); however, T3 was found to be statistically at par with T7 (RDF + nano DAP foliar spray at 1.0 %). In contrast, the control treatment (T0) recorded the minimum nutrient uptake.

The improved response may be due to nano-zinc application, which improved N, P and K uptake and their translocation to grain and stover through improved foliar absorption and nutrient use efficiency. On the other hand, foliar application of nano-DAP may have improved N, P and K uptake in maize grain and stover by supplying readily available N and P, which supported root activity, nutrient absorption and efficient translocation of nutrients within the plant. In contrast, the control treatment recorded the minimum nutrient uptake due to poor nutrient availability, limited absorption and reduced nutrient translocation to grain and stover.

The findings of the nutrient accumulation are in line with the earlier studies as results of fertilisation balance in maize materials revealed the positive effects on nutrient uptake efficiency (33, 34).

Zinc enrichment in spring maize (mg kg^{-1})

The combined application of foliar zinc and nano macronutrients significantly influenced zinc concentration in both grain and stover of spring maize, as shown in Fig. 8. The maximum amount of zinc, 38.92 mg kg^{-1} , was observed in T3 (RDF + foliar spray nano-zinc at 1.0 %), which highlights the beneficial effect of zinc in enhancing nutrient absorption and its efficient translocation within the crop. T7 (RDF + 1.0 % foliar application of nano-DAP) was statistically comparable with T3 at a value of 36.41 mg kg^{-1} , indicating that the adequate supply of P enhances the uptake of zinc due to enhanced root activity and metabolic activity. The control (T0) showed the lowest level of grain zinc (21.84 mg kg^{-1}), which means that the nutrient-deficient conditions did not allow the unrestricted availability of zinc.

The same tendency was noted with stover, with T3 having the highest concentration of zinc (44.87 mg kg^{-1}), which remained statistically comparable with T7 (42.58 mg kg^{-1}). The lowest zinc concentration in stover (26.73 mg kg^{-1}) was recorded under the control treatment. The relatively greater zinc retention in stover than in grain is indicative of reduced remobilisation in grain filling. The current results are very similar to the previous research (35, 36), which demonstrated that foliar zinc application has a significant effect in increasing the zinc concentration and total uptake of zinc in maize grain and maize stover, as it leads to a high absorption and translocation rate.

Economics

The economic analysis presented in Table 3 revealed clear differences among the nutrient management treatments evaluated in spring maize. Table 3 showed significant differences in the economics of spring maize among the nutrient management treatments. T3 (RDF + Nano-zinc at 1.0 %) recorded the highest gross return (Rs 125400 ha^{-1}), net return (Rs 76400 ha^{-1}) and benefit-cost ratio (2.56). T7 remained statistically at par with T3, with a gross return of Rs 116100 ha^{-1} , net return of Rs 67100 ha^{-1} and B : C ratio of 2.37. The better economic performance of these treatments was mainly due to higher grain and stover yields, which more than compensated for the additional cost of nano-fertiliser application. In contrast, the control treatment recorded the lowest gross return (Rs 55200 ha^{-1}), net return (Rs 10200 ha^{-1}) and B : C ratio (1.23), showing poor economic viability under nutrient-deficient conditions. Similar higher economic returns with nano-fertiliser application in maize were also reported in earlier studies (37, 38).

Table 3. Impact of foliar nutrition with nano zinc and nano macro nutrients on the economics of spring maize

Symbol	Treatments	Gross return (rs/ha)	Net return (rs/ha)	B : C ratio
T0	Control	55200.00	10200.00	1.23
T1	RDF	68600.00	21600.00	1.46
T2	RDF + Foliar spray of nano-zinc at 0.5 %	85966.67	37466.67	1.77
T3	RDF + Foliar spray of nano-zinc at 1.0 %	125400.00	76400.00	2.56
T4	RDF + Foliar spray of nano-urea at 0.5 %	74400.00	25900.00	1.53
T5	RDF + Foliar spray of nano-urea at 1.0 %	71900.00	23400.00	1.48
T6	RDF + Foliar spray of nano-DAP at 0.5 %	97400.00	48900.00	2.01
T7	RDF + Foliar spray of nano-DAP at 1.0 %	116100.00	67100.00	2.37
T8	RDF + Foliar spray of nano-K ₂ O at 0.5 %	67500.00	19500.00	1.41
T9	RDF + Foliar spray of nano-K ₂ O at 1.0 %	77300.00	29300.00	1.61
SE(m)±		1,624.27	1,624.27	0.033
C.D. ($p \leq 0.05$)		4,863.35	4,863.35	0.099

DAP: diammonium phosphate; RDF: recommended dose of fertiliser.

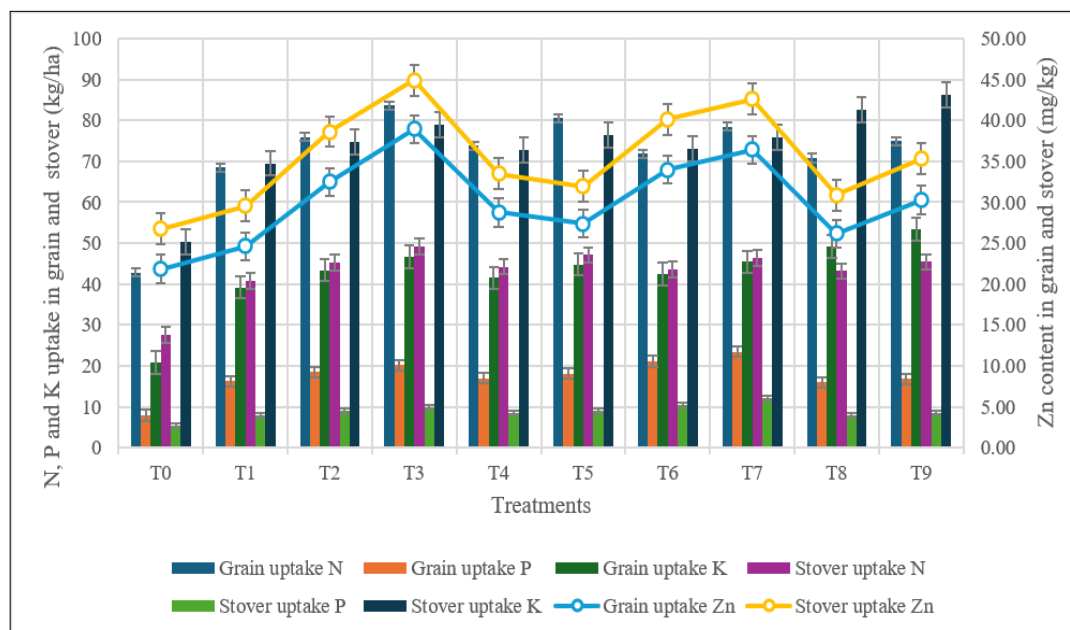


Fig. 8. Influence of foliar application of nano zinc and nano macro nutrients on the uptake of N, P and K and zinc content in spring maize.

Conclusion

The present investigation revealed that foliar spraying of nano-fertilisers at the critical growth stages of spring maize significantly improved crop growth, physiological efficiency, nutrient uptake and yield performance. Among the treatments, T3 (100 % recommended dose of fertilisers (RDF) + nano-zinc at 1.0 %) gave the best results for plant height, chlorophyll content, grain yield, zinc accumulation and economic returns under Punjab conditions. T7 (100 % RDF + nano diammonium phosphate (DAP) at 1.0 %) also showed strong performance and was statistically comparable with T3 for several important traits. Overall, the study indicates that nano-zinc applied along with the recommended fertiliser dose is a promising and sustainable option for spring maize production. Since the experiment was conducted in a single spring season (2025) under the agro-climatic conditions of Punjab, the findings should be interpreted with caution, as treatment responses may vary with season and environment. Future research should test these treatments in different locations and seasons, refine the dose and timing of application and examine their long-term effects on soil health, environmental safety and grain biofortification under stress conditions.

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Authors' contributions

US designed and executed the field experiment, collected and compiled the data, performed the statistical analysis and drafted the original manuscript. SS provided overall supervision, contributed to the development of the methodology and critically revised the manuscript for intellectual content. AK provided constructive guidance and valuable suggestions during the study. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used BioRender to create scientific illustrations, VOSviewer to generate bibliometric mapping and network visualisations and Microsoft Excel to prepare tables and graphical representations of data. Jenni AI was used solely for language editing and improving readability during manuscript preparation. After using these tools, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

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