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RESEARCH ARTICLE

Harnessing green synthesized zinc oxide nanoparticles for enhancement of sweet corn yield and quality

Sarin S[1], S Sanbagavalli[1*], P Janaki[2], P Geetha[3] & S K Rajkishore[4]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Nammazhvar Organic Farming Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Centre for Post-Harvest Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Department of Renewable Energy Engineering, Agricultural Engineering College & Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: sanbagavalli.s@tnau.ac.in

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Abstract

Sweet corn (*Zea mays* var. *saccharata*), cherished globally for its sweet taste and nutritional richness, is sensitive to zinc availability-a key micronutrient vital for enzymatic activity, photosynthesis and kernel development. Despite its importance, zinc deficiency in agricultural soils remains a significant barrier to enhancing crop yield and nutritional quality. This study explores the efficacy of foliar-applied green-synthesized zinc oxide nanoparticles (ZnO NPs) using *Moringa oleifera* leaf extract in enhancing sweet corn yield and quality under field conditions at Tamil Nadu Agricultural University, Coimbatore, during the Kharif season of 2024, employing a Randomized Block Design with seven treatments, varying ZnO NP concentrations from 100 to 600 ppm, applied at 40 and 60 days after sowing (DAS). The findings revealed that foliar application of ZnO NPs at 500 ppm significantly enhanced yield parameters, including cob weight (269.9 g), grain yield (10277 kg/ha), green cob yield (16195 kg/ha) and green fodder yield (16393 kg/ha) along with quality attributes such as total soluble solids (16.33 °Brix), total sugars (12.07 %) and carbohydrate content (25.08 %). Enhanced zinc uptake (357.5 g/ha) and recovery efficiency (50.63 %) were also recorded. Correlation analysis also revealed strong positive associations between yield traits, such as cob weight, grain yield and green fodder yield, with zinc uptake and content in grains. These results underscore the potential of ZnO NPs in optimizing zinc bioavailability to bolster sweet corn yield and nutritional value and thereby positioning ZnO NPs as a promising and sustainable biofortification strategy.

Keywords

foliar application; quality; sweet corn; yield; zinc oxide nanoparticles

Introduction

Sweet corn (*Zea mays* var. *saccharata*) is a widely cultivated cereal crop valued for its nutritional richness, characterized by a high sugar concentration and essential micronutrients. In recent years, increasing the nutritional quality and yield of sweet corn has gained significant attention, particularly using novel agronomic practices such as biofortification. As a vital micronutrient, zinc supports various physiological functions in plants, including enzyme activation, chlorophyll production, pollen fertility and kernel formation. Despite its importance, zinc deficiency is still a widespread problem in agricultural soils, limiting crop productivity and leading to nutritional deficiencies in human populations consuming zinc-deficient produce (1, 2).

Nanotechnology involves the manipulation of materials at the nanoscale (1-100 nm), enabling unique physicochemical properties that enhance their reactivity and efficiency. In agriculture, nanoscale fertilizers, including zinc oxide nanoparticles (ZnO NPs), improve nutrient solubility, uptake and targeted delivery, reducing losses and enhancing plant metabolism. Green synthesis of these nanoparticles using biological agents ensures environmental sustainability while maintaining effectiveness. By leveraging these advancements, nanotechnology offers a promising approach to addressing micronutrient deficiencies and improving crop productivity. Eco-friendly synthesized ZnO NPs have demonstrated potential in enhancing plant health, yield and quality attributes. The application of ZnO NPs (15-30 nm) as a foliar spray enables direct and efficient nutrient uptake, minimizing environmental losses like soil-related limitations such as immobilization and leaching (3-5). Foliar-applied ZnO NPs have been reported to improve photosynthetic activity, metabolic enzyme activity and stress tolerance in crops like rice, wheat and maize, leading to increased grain yield and nutritional quality (6, 7).

Sweet corn production is particularly sensitive to zinc availability due to the micronutrient's critical role during the reproductive stages. Zinc improves pollen viability at tasseling, a key determinant of successful fertilization and grain development (8). Additionally, zinc influences the synthesis and transport of carbohydrates and secondary metabolites, which are vital for kernel quality and storage (8, 9). Research has shown that timely zinc application enhances chlorophyll synthesis and photosynthesis, leading to better light absorption and carbohydrate accumulation (5, 10). This is because zinc stabilizes thylakoid membranes in chloroplasts, preventing degradation of chlorophyll and improving photosynthetic efficiency. Also, zinc deficiency reduces ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO) activity, limiting CO_2 fixation and reducing photosynthetic rate. Adequate and timely zinc supply ensures optimal production of photosynthetic pigments, improving light absorption and energy conversion. Nevertheless, research on the impact of foliar-applied ZnO NPs on sweet corn remains limited, particularly when applied at key phenological stages like 40 and 60 days after sowing (DAS). This study investigates the impact of foliar application of green-synthesized ZnO NPs on the yield and quality of sweet corn grown under field conditions. The nanoparticles were eco-friendly synthesized using *Moringa oleifera* leaf extract as a reducing agent, ensuring a sustainable approach to nutrient delivery. The findings aim to offer valuable insights into the potential of ZnO NPs as a sustainable agronomic practice for enhancing sweet corn productivity and nutritional quality.

Materials and Methods

Experimental Site and experiment details

The field study was carried out in *Kharif* 2024 at the Eastern Block farm (11°00'59''N, 76°56'05''E), Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore. The experiment was laid out in Randomized Block Design with seven treatments replicated thrice. The treatments given were different doses of green synthesized zinc oxide nanoparticles. All the treatments were foliar applied at 40 DAS and 60 DAS. The treatments were T_1: Foliar application of synthesized zinc oxide nanoparticles @ 100 ppm, T_2: Foliar application of synthesized zinc oxide nanoparticles @ 200 ppm, T_3: Foliar application of synthesized zinc oxide nanoparticles @ 300 ppm, T_4: Foliar application of synthesized zinc oxide nanoparticles @ 400 ppm, T_5: Foliar application of synthesized zinc oxide nanoparticles @ 500 ppm, T_6: Foliar application of synthesized zinc oxide nanoparticles @ 600 ppm, T_7: Control (No zinc application).

Planting material and nanoparticles

The sweet corn variety Sugar 75 was purchased from Syngenta India Ltd. For this study, ZnO NPs were green synthesized, characterized and produced in bulk at the Department of Agronomy, Tamil Nadu Agricultural University, utilizing *Moringa oleifera* leaf extract as a reducing agent through the co-precipitation method. The synthesized zinc oxide nanoparticles had an average crystallite size of 53.88 nm (Unpublished data).

Parameters studied

Five sample plants from each treatment plot were tagged and used for recording observations. The yield parameters like cob weight, number of kernel rows, number of kernels per row, total number of kernels per cob, 100 seed weight, grain yield, stover yield and harvest index of sweet corn were observed. The quality parameters analyzed in the study included total soluble solids (TSS), total sugars, reducing sugars, total carbohydrates and starch content, using fresh kernels. Each parameter was determined following the standard protocols (11). Given below is an elaboration of the procedures:

Total Soluble Solids (TSS): TSS was measured using a hand refractometer. A small amount of pulp extracted from fresh kernels was placed on the refractometer prism and the reading was taken in °Brix, which directly indicates the percentage of dissolved solids.

Total Sugars and Reducing Sugars: Total sugars were estimated using the phenol-sulfuric acid method, a colorimetric assay where sugar reacts with phenol and concentrated sulfuric acid to produce a green color measurable at 630 nm. Reducing sugars were determined using the DNS (dinitrosalicylic acid) method, where reducing sugars reduce 3,5-dinitrosalicylic acid to form a colored complex, quantified spectrophotometrically at 510 nm. Both were estimated using the formula,

Sugars (%) = (X/Volume of aliquot) x (Total volume of extract/ weight of sample) ×100 (Eqn. 1)

X= concentration of glucose corresponding to absorbance value at 630 nm (total sugars) and 510 nm (reducing sugars) from standard curve.

Total Carbohydrates: Total carbohydrates were quantified using the anthrone method.

Carbohydrate Content (%) = (mg of glucose corresponding to absorbance value at 490 nm from graph/Volume of test sample) ×100 (Eqn. 2)

Starch Content: Starch content was estimated after enzymatic or acid hydrolysis to glucose, which was then determined using the anthrone reagent method.

Starch Content (%) = concentration of glucose corresponding to absorbance value at 630 nm from standard curve × 0.9 (Factor) (Eqn. 3)

The zinc content in grain (ppm) was estimated using ICP-MS. Zinc uptake (g/ha) was computed with the zinc content and grain yield. Zinc recovery efficiency was computed using the formula given by (12), as follows:

Recovery efficiency = {Zn uptake in Zn treated plot (g/ha) - Zn uptake in control plot (g/ha)}/ Zn applied (g/ha) (Eqn. 4)

Statistical analysis

Analysis of variance (ANOVA) technique was used to analyse the significance of different treatments and the LSD test at $P \leq 0.05$ was used to compare treatment means by using GRAPES (General R based Analysis Platform Empowered by Statistics) computer-based software (13). Correlation analysis was done using the R software.

Results and Discussion

Yield parameters

The foliar applied zinc oxide nanoparticles produced significant results on the yield aspects of sweet corn. Highest test weight (34.33 g) in sweetcorn was recorded in foliar application of zinc oxide nanoparticles @ 500 ppm at 40 & 60 DAS (T_5).

The cob weight (269.9 g), grain yield (10277 kg/ha), green cob yield (16195 kg/ha) and green fodder yield (16393 kg/ha) of sweetcorn was significantly higher in foliar application of zinc oxide nanoparticles @ 500 ppm at 40 & 60 DAS (T_5). It was statistically on par with foliar application of zinc oxide nanoparticles @ 400 ppm at 40 & 60 DAS (T_4), for cob weight (258.9 g), grain yield (9805 kg/ha), green cob yield (15535 kg/ha) and green fodder yield (16349 kg/ha).

The lowest green fodder yield (15152 kg/ha) was recorded in control plot (T_7). Lesser 100 seed weight (26.88 g) was observed in control plot (T_7) and was comparable with foliar application of zinc oxide nanoparticles @ 100 ppm at 40 & 60 DAS (T_1).

The lower values of cob weight, grain yield and green cob yield (225.4 g, 10277 kg/ha and 13596 kg/ha respectively) were recorded in control plot. These were on par with the foliar application of zinc oxide nanoparticles @ 100 ppm at 40 & 60 DAS (T_1) and foliar application of zinc oxide nanoparticles @ 200 ppm at 40 & 60 DAS (T_2). The data pertaining to yield parameters are presented in Table 1, 2, 3. The harvest index in sweet corn was not significantly influenced by the zinc oxide nanoparticle treatments. The value range ranged between 0.473 to 0.497.

The number of kernel rows, number of kernels per row and total number of kernels per cob were not significantly influenced by the various zinc oxide nanoparticle dosages. The values ranged from 13.93 to 15.00 (number of kernel rows), 39.73 to 46.73 (number of kernels per row) and 542.27 to 665.07 (total number of kernels per cob).

Table 1. Effect of different doses of zinc oxide nanoparticles on cob weight (g) and 100 seed weight (g) of sweetcorn at harvest

Treatments	Cob weight (g)	100 seed weight (g)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	236.7	28.29
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	239.9	29.57
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	249.8	31.03
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	258.9	31.59
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	269.9	34.33
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	246.8	30.18
T_7: Control	225.4	26.88
SE(d)	8.68	0.92
CD (P=0.05)	18.901	2.003

Table 2. Effect of different doses of zinc oxide nanoparticles on green cob yield (kg/ha) and green fodder yield (kg/ha) of sweetcorn at harvest

Treatments	Green cob yield (kg/ha)	Green fodder yield (kg/ha)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	14202	15493
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	14393	15510
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	14985	15896
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	15535	16349
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	16195	16393
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	14804	15811
T_7: Control	13596	15152
SE(d)	520.31	298.61
CD (P=0.05)	1133.654	650.621

Table 3. Effect of different doses of zinc oxide nanoparticles on grain yield (kg/ha) and Harvest Index of sweetcorn at harvest

Treatments	Grain yield (kg/ha)	Harvest Index
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	9223	0.478
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	9256	0.481
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	9550	0.485
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	9805	0.487
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	10277	0.497
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	9487	0.483
T_7: Control	8779	0.473
SE(d)	286.11	0.01
CD (P=0.05)	623.372	NS

Zinc plays an integral role in auxin metabolism, carbohydrate synthesis and protein metabolism, which directly influence grain filling and test weight (14). The significantly higher test weight in T_5 reflects improved kernel density and quality, likely resulting from enhanced nutrient uptake and translocation facilitated by ZnO NPs. As previously reported, foliar zinc applications of 250 and 500 ppm at 20 and 40 DAS enhance photosynthetic efficiency and the allocation of assimilates to reproductive structures, thereby improving kernel weight (15).

The increased cob weight and grain yield in T_5 may be attributed to enhanced enzymatic activity and efficient nutrient transport, promoting superior cob and kernel development. Similarly, ZnO NPs have been found to enhance cell elongation and promote starch deposition in grains (5). The enhancement in grain yield may also be linked to the increase in kernel weight and number compared to the control, likely due to improved pollen viability facilitated by sufficient zinc availability during the tasseling stage, which is critical for effective fertilization and subsequent grain development (8). The substantial increase in fodder yield in T_5 further highlights zinc's role in promoting vegetative growth and overall plant vigor. Zinc's involvement in cell wall synthesis and protein metabolism likely contributed to the observed biomass increase (16).

Furthermore, the comparable performance of T_4 (ZnO NPs @ 400 ppm) to T_5 for cob weight and grain yield indicates diminishing returns beyond optimal zinc concentrations, potentially due to nutrient uptake saturation or mild toxicity at excessive levels.

Conversely, the control treatment (T_7) recorded the lowest test weight, cob weight, grain yield and green fodder yield stressing zinc's vital role in physiological and biochemical processes necessary for optimal plant growth and yield. These findings align with previous research indicating that zinc deficiency impairs enzymatic function and photosynthetic capacity, ultimately reducing biomass and grain yield (17).

Interestingly, ZnO NP treatments did not significantly influence the harvest index, number of kernel rows, kernels per row, or total kernels per cob. The harvest index ranged from 0.473 to 0.497, indicating that zinc primarily enhanced biomass accumulation without affecting the distribution of assimilates between economic and biological yields. Similarly, the lack of significant variation in kernel rows and kernel numbers across treatments suggests that zinc or zinc oxide nanoparticles do not affect floral development or kernel set but instead enhances kernel filling and weight, as observed in T_5 and T_4. These findings are consistent with previous research which reported that zinc primarily improves kernel quality rather than kernel number in rice (18). Foliar zinc application has been shown to enhance grain yield, 100-grain weight and other quality parameters in rice, suggesting that micronutrient applications can improve grain filling and quality without significantly altering kernel numbers (2). Similar findings in sweet corn yield and yield attributes were also noted (19).

Quality parameters

The data pertaining to the effect of zinc oxide nanoparticles on sweet corn quality is presented below (Tables 4 - 7). Statistically superior values of TSS (16.33 °brix) and total sugars (12.07 %) were observed in foliar application of zinc oxide nanoparticles @ 500 ppm at 40 & 60 DAS (T_5).

Carbohydrate content (25.08 %) and starch content were higher (24.87 %) in foliar application of zinc oxide nanoparticles @ 500 ppm at 40 & 60 DAS (T_5) and was comparable with foliar application of zinc oxide nanoparticles @ 400 ppm (23.60 % of carbohydrate and 25.14 % of starch) at 40 & 60 DAS (T_4). Zinc is a cofactor for several enzymes

Table 4. Effect of different doses of zinc oxide nanoparticles on TSS (°brix) and total sugars (%) of sweetcorn at harvest

Treatments	TSS (°brix)	Total sugars (%)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	13.00	8.57
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	13.33	8.83
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	14.00	9.02
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	14.17	9.30
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	16.33	12.07
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	14.17	9.30
T_7: Control	12.83	8.28
SE(d)	0.69	0.53
CD (P=0.05)	1.506	1.162

Table 5. Effect of different doses of zinc oxide nanoparticles on carbohydrate content (%) and starch content (%) of sweetcorn at harvest

Treatments	Carbohydrate content (%)	Starch content (%)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	21.70	19.46
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	22.27	21.79
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	22.32	21.80
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	23.60	23.02
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	25.08	24.87
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	22.59	22.05
T_7: Control	20.91	18.32
SE(d)	0.71	0.85
CD (P=0.05)	1.546	1.850

Table 6. Effect of different doses of zinc oxide nanoparticles on reducing sugars (%) and zinc content in kernel (ppm) of sweetcorn at harvest

Treatments	Reducing sugars (%)	Zinc content (ppm)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	4.66	29.40
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	4.98	31.87
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	5.12	33.24
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	5.35	34.25
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	5.41	34.78
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	5.04	33.83
T_7: Control	4.41	28.02
SE(d)	0.19	0.69
CD (P=0.05)	0.409	1.511

Table 7. Effect of different doses of zinc oxide nanoparticles on zinc uptake (g/ha) and zinc recovery efficiency (%) of sweetcorn at harvest

Treatments	Zinc uptake (g/ha)	Zinc recovery (%)
T_1: Foliar application of zinc oxide nanoparticles @ 100 ppm	271.3	50.63
T_2: Foliar application of zinc oxide nanoparticles @ 200 ppm	295.4	49.40
T_3: Foliar application of zinc oxide nanoparticles @ 300 ppm	316.8	47.20
T_4: Foliar application of zinc oxide nanoparticles @ 400 ppm	335.5	44.75
T_5: Foliar application of zinc oxide nanoparticles @ 500 ppm	357.5	44.58
T_6: Foliar application of zinc oxide nanoparticles @ 600 ppm	320.9	24.96
T_7: Control	245.9	0.00
SE(d)	11.46	
CD (P=0.05)	24.963	

involved in carbohydrate metabolism, including fructose-1,6-bisphosphatase and aldolase, which regulate starch and carbohydrate synthesis. Zinc also influences ADP-glucose pyrophosphorylase (AGPase) and starch synthase which are key enzymes in starch biosynthesis. The increased zinc concentration in T_5 and T_4 treatments might have facilitated higher enzymatic activity, leading to improved carbohydrate accumulation and starch deposition in developing kernels.

Foliar application of zinc oxide nanoparticles @ 500 ppm at 40 & 60 DAS (T_5) recorded higher value of reducing sugars (5.41 %), zinc content in grain (34.78 ppm) and zinc uptake (357.5 g/ha). Reducing sugars in T_5 was on par (5.35 %) with foliar application of zinc oxide nanoparticles @ 400 ppm at 40 & 60 DAS (T_4), foliar application of zinc oxide nanoparticles @ 300 ppm (5.12 %) at 40 & 60 DAS (T_3) and foliar application of zinc oxide nanoparticles @ 600 ppm (5.04 %) at 40 & 60 DAS (T_6). The higher zinc content in grain recorded in T_5, was statistically on par with foliar application of zinc oxide nanoparticles @ 400 ppm (34.25 ppm) at 40 & 60 DAS (T_4) and foliar application of zinc oxide nanoparticles @ 600 ppm (33.83 ppm) at 40 & 60 DAS (T_6). Zinc uptake of T_5 was comparable with foliar application of zinc oxide nanoparticles @ 400 ppm (335.5 g/ha) at 40 & 60 DAS (T_4) alone.

The lower value of TSS (12.83 °brix) and total sugars (8.28 %) was observed in control plot (T_7), which was comparable with all the other treatments except T_5. Lesser carbohydrates (20.91 %) and reducing sugars (4.41%) were found in control plot (T_7), which was on par with foliar application of zinc oxide nanoparticles @ 100 ppm at 40 & 60 DAS (T_1) and foliar application of zinc oxide nanoparticles @ 200 ppm at 40 & 60 DAS (T_2). Lesser starch content (18.32 %) and zinc content in grain (28.02 ppm) was recorded in control plot (T_7), which was comparable with foliar application of zinc oxide nanoparticles @ 100 ppm at 40 & 60 DAS (T_1).

Lowest zinc uptake (245.9 g/ha) was also recorded in control plot. Zinc recovery efficiency was highest (50.63 %) in foliar application of zinc oxide nanoparticles @ 100 ppm at 40 & 60 DAS (T_1) and lowest (24.96 %) in foliar application of zinc oxide nanoparticles @ 600 ppm (T_6).

Zinc is vital for carbohydrate and starch synthesis, serving as a cofactor for enzymes such as carbonic anhydrase and fructose bisphosphate aldolase, which play key roles in photosynthetic carbon fixation and carbohydrate metabolism (17). The notable increase in starch content observed in T_5 could be attributed to improved photosynthetic efficiency induced by ZnO NPs, likely enhancing the biosynthesis and storage of starch in kernels. Likewise, the elevated carbohydrate content in T_5 indicates better mobilization of carbohydrates from source tissues to sink tissues during grain filling. Similar results were reported in maize as well (15). The elevated TSS and total sugars in T_5 can be attributed to zinc's pivotal role in sugar metabolism. Zinc is critical for the activity of sucrose synthase, an enzyme essential for converting sucrose into hexose sugars. Furthermore, zinc-mediated stress signaling pathways may have stimulated the production of secondary metabolites, thereby bringing in more soluble sugars and enhancing kernel quality (5). Adequate zinc levels regulate sugar metabolism genes, enhancing the conversion of starch into soluble sugars (sucrose, glucose and fructose) during grain filling. A 500-ppm foliar spray might have promoted higher starch hydrolysis than the lower zinc concentrations.

The increase in reducing sugars, grain zinc content and zinc uptake in T_5 can be linked to the efficient uptake and translocation of zinc from foliage to grains through the phloem. Zinc, absorbed as Zn^{2+} ions via stomatal pores, is actively transported to sink tissues by transport proteins such as ZIP (Zinc-Iron Permease) and ZRT (Zinc regulated transporter) (17). Additionally, foliar application ensures the timely availability of nutrients during critical growth phases like tasselling and grain filling, resulting in improved nutrient accumulation especially zinc, in kernels (18). ZnO NPs have also been recognized for their role in triggering stress responses that facilitate nutrient mobilization and storage (5). The zinc recovery declined notably as zinc application levels increased, which can be attributed to the commonly observed inverse relationship between nutrient utilization and the rate of application. The decline in recovery with increasing zinc levels indicates a reduced efficiency of utilization per unit of application, though zinc continues to contribute to crop growth and yield. High recovery efficiency is typically achieved at optimal application rates, which balance supply and plant uptake. Excessive application may not improve nutrient recovery but can still positively influence plant performance until the point of toxicity. Similar recovery trends have been observed in previous studies (20, 21).

The performance of T_4 (ZnO NPs @ 400 ppm) was statistically comparable to T_5 concerning starch content, reducing sugars and kernel zinc content, suggesting that increasing zinc concentration beyond optimal levels does not proportionally enhance quality attributes. Excessive zinc application may induce mild toxicity due to oxidative stress following ROS formation, thereby reducing nutrient bioavailability and other physiological functions (22). Nanoparticle agglomeration reduces the surface area of nanoparticles available for absorption by plant tissues. Nanoparticles typically improve nutrient uptake by increasing surface interaction with plant cells (23, 24). When agglomerated, the particles' ability to be absorbed through stomata or leaf cuticles decreases, thus reducing the bioavailability of zinc to the plant. Once inside the plant, agglomerated nanoparticles may not be transported effectively to areas where they are needed, such as developing grains (23). This could be the reason for reduced yield and quality in T_6 (600 ppm). The control treatment (T_7) consistently recorded lower values for all parameters, highlighting zinc's essential role in maintaining plant metabolic processes. These findings are consistent with prior research indicating that foliar-applied ZnO NPs enhance carbohydrate and sugar synthesis by improving chlorophyll content, photosynthetic efficiency and enzyme activities. Similar outcomes have been observed in sweet corn (25), in rice (18) and maize (15).

Correlation analysis

The correlation matrix demonstrated significant positive relationships between major yield and quality traits in sweet corn subjected to different ZnO NP treatments (Fig. 1). Cob weight exhibited a strong positive correlation with grain yield (r = 1), green cob yield (r = 1) and green fodder yield (r = 0.98), clearly indicating that ZnO-NP application contributed to biomass accumulation and yield enhancement. Similarly, grain zinc content showed a strong correlation with cob weight (r = 0.91), demonstrating effective zinc translocation from foliage to grains.

Notably, total soluble solids (TSS) and total sugar content were positively correlated with yield traits but showed only moderate correlations with Zn uptake, indicating that ZnO-NP treatments improved sweetness and quality but were not the sole determinants of sugar accumulation. Overall, these results highlight the beneficial role of ZnO-NP application in improving quality and yield

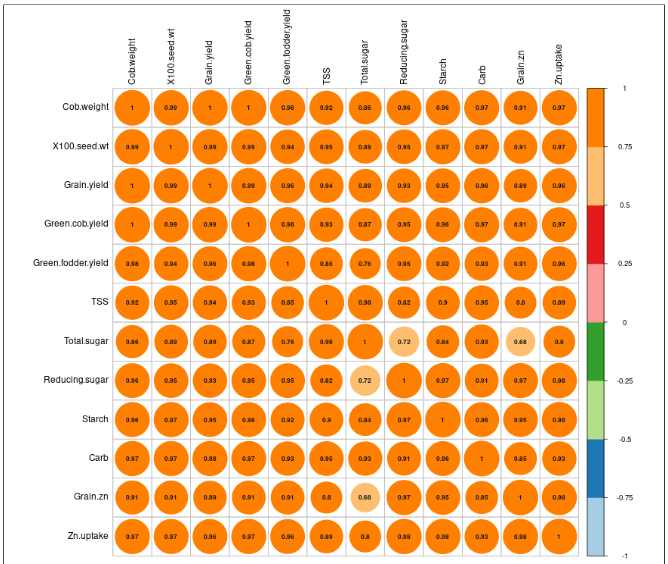

Fig. 1. Correlation plot showing relationship between major yield and quality parameters of sweet corn.

parameters up to an optimal concentration.

Conclusion

The results of this experiment conducted in sweet corn indicate that foliar application of zinc oxide nanoparticles @ 500 ppm at 40 and 60 DAS proved to be better performing in terms of yield and quality parameters. These advantages arise from timely direct intake of zinc oxide nanoparticles through leaves and zinc's direct impact on plant metabolism, along with its role in promoting enzyme activation, protein synthesis and photosynthesis. Consequently, zinc oxide nanoparticles offer a promising, sustainable method to improve kernel quality and yields of sweet corn.

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Authors' contributions

SS[1] carried out experiments, recording observations, analysis of the data and preparation of the manuscript. SS[2] guided the research by formulating the research concept and reviewed and approved the final manuscript. PJ shared their inputs for upscaling and facilitated analysis. Also helped in editing summarizing and revising the manuscript. PG shared their inputs for upscaling and facilitated analysis. Also helped in editing summarizing and revising the manuscript. SKR guided research in nanoparticle synthesis and application and helped in editing summarizing and revising the manuscript. (SS[1] - Sarin S and SS[2] - S Sanbagavalli)

Compliance with ethical standards

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

Ethical issues: None

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