

Field evaluation of Zinc oxide - graphene oxide bio nanocomposite fertigation strategy for improving growth, yield and soil fertility in Zea mays L.

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Research Article

Keywords: Zea mays L. (maize), soil biological activity, Zinc oxide - graphene oxide nanocomposite, soil fertility, crop yield

Posted Date: January 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8375014/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Cereal Research Communications on April 16th, 2026. See the published version at <https://doi.org/10.1007/s42976-026-00800-5>.

Abstract

Maize productivity enhancement is one of the leading areas of research in the past several decades. Sustaining soil health has to be considered parallel to the yield in cereal crop improvement. In this study, a Zinc oxide - graphene oxide (ZnO/GO NC) bio nanocomposite was evaluated for its ability to improve growth performance, yield formation, and soil biological activity in maize (*Zea mays* L.). Twelve fertigation treatments comprising of nanocomposites and individual nanoparticles were arranged in a randomized complete block design (RCBD). Standard zinc treatments and vermicompost treatment were used to establish comparison of obtained results. Crop growth quality parameters were assessed through germination, plant height, leaf development and phenological changes like tasseling and silking. Yield components such as cob length, biomass accumulation, 100-grain weight, and yield were recorded to understand contributions to cereal productivity. Post-harvest soil assessment was focused on physicochemical attributes, macronutrients, micronutrients and biological indicators like dehydrogenase activity (DHA) and microbial biomass carbon (MBC). 2000 ppm of ZnO/GO NC was shown to improve maize growth and yield traits without imparting a negative impact on soil quality measurements. The values generated for DHA and MBC assay showed an enhanced soil functional quality and no detrimental effects on microbial activity. Overall, the study demonstrates that this treatment can support both yield enhancement and soil quality development.

Introduction

Maize is widely grown in many parts of the world. Apart from the usage in food and animal feed, maize also has several other industrial applications. Over the past 25 years, there is a huge rise in maize yield and cultivation area. It is the leading crop by volume worldwide and it is necessary to sustain the growth by investing in research and development (Erenstein et al. 2022). The yield in maize cultivation is not realized completely in India. Some of the causes identified were poor fertilizer use, issues encountered while adopting newer technologies and nutrient imbalances. Nutrient management is the key aspect to maximize yield of maize crops (Sharma et al. 2024). Integrated nutrient management approaches are suggested to maintain the soil quality and sustainability while increasing the crop yield (Gezahegn 2021).

Zinc is a vital micronutrient for maize crop. Zinc deficiency in maize cultivation can result in improper growth and can significantly reduce grain yield. Zinc fertigation has been shown to improve plant nutrient uptake and overall productivity. Grain qualities like nutrient content and kernel development has also shown improvement in case of Zinc supplementation (Suganya et al. 2020). Studies support adopting dynamic fertigation strategies instead of a one-time application depending on the plant needs timely nutrient supplementation throughout its growth cycle. As a growing plant, maize needs multiple nutrients at various stages of growth. It becomes imperative to understand the need of the plant and supply essential nutrients appropriately (Bojtor et al. 2021). Nano spray formulations of Zinc was shown to improve both vegetative and reproductive characteristics of maize. A yield gain of up to 20% was realized with optimized Zinc fertigation regime in maize (Badawi et al. 2022).

For sustaining maize cultivation, a strong emphasis has to be laid on enhancing the soil fertility. Several researches underline the importance of soil health, nutrient recycling and minimizing environmental losses for sustainable crop production. Soil management strategies need to be developed along with the crop development strategies to ensure long term productivity (Havlin and Heiniger 2020). Using maize as a model plant, carbon based nanoparticles demonstrated the potential to improve soil parameters along with an improvement in plant growth and yield characteristics (Zhao B et al. 2021).

This current study focussed on the gaps in research in finding an effective nanocomposite based fertigation strategy to improve plant characteristics and soil parameters simultaneously. Field performance of *Zea mays*

L. using a ZnO/GO NC fertigation was assessed to identify an efficient and sustainable nanocomposite based fertilizers to promote efficient and sustainable maize production.

Materials and methods

Experimental location

The field trial was performed during the monsoon season (Aadipattam/Kharif known locally, sown on 5th June, 2025) at the agricultural farm located in karamadai, Tamil Nadu, India (11.238097723260852°N, 76.94383098540787°W). The region is classified to have a tropical climate. The average temperature recorded was 27°C (warm, humid and rainy at times) and rainfall of about 80–90 mm during the cropping period.

Soil characteristics measurement

As per the reports by Tamil Nadu Agricultural University (TNAU), the soil was classified as red loam and was sampled by quadrant during method before sowing to determine baseline properties. Standard soil analyses were carried out for pH, electrical conductivity (EC), macronutrients (Carbon, Nitrogen, Phosphorus, Potassium and Sulphur) and micronutrients (Zinc, Iron, Manganese and Copper). Biological activity was measured using dehydrogenase activity and microbial biomass carbon. Dehydrogenase (DHA) activity in soil was measured using the TTC reduction method and was expressed as $\mu\text{g TPF g}^{-1} \text{ h}^{-1}$ (Casida et al. 1964). Microbial biomass carbon (MBC) was determined using the chloroform fumigation–extraction technique using a k_{C} factor of 0.45 (Vance et al. 1987).

Nanocomposite preparation

A bio nanocomposite of zinc oxide (ZnO) and graphene oxide (GO) was prepared using microbial reduction technique (data under publication). Zinc oxide nanoparticle (ZnO NP) was prepared from a solution of 0.1 M Zinc nitrate in 0.4 M sodium hydroxide was reduced using cultured broth of actinomycetes (*Streptomyces enissocaesilis*). Graphene oxide nanoparticle (GO NP) prepared from graphite using modified hummer's method was reduced in the presence of spent broth and together. Both ZnO NP and GO NP were further reduced to form bio nanocomposite (ZnO/GO NC) used in this study. The nanocomposite was characterized and initial pot studies using *Vigna radiata* were conducted to evaluate the appropriate dosage to be used for field trials.

Experimental Design

The twelve treatments in three replicates were assigned to each plot in a randomized complete block design (RCBD). Table 1 summarizes the treatments performed in this study. Each plot measured 1.5 m × 2.4 m.

Table 1
Treatment details and fertigation used for field trials

Treatments		Fertigation
T1	No fertigation control	Basal fertigation (67.5:62.5:25 kg/ha of N:P ₂ O ₅ :K ₂ O) before sowing
T2	2000 ppm ZnO NP	Basal fertigation + 6g ZnO NP/ 3L (per plot) on 15 & 45 DAS
T3	3000 ppm ZnO NP	Basal fertigation + 9g ZnO NP / 3L (per plot), on 15 & 45 DAS
T4	4000 ppm ZnO NP	Basal fertigation + 12g ZnO NP / 3L (per plot), on 15 & 45 DAS
T5	2000 ppm GO NP	Basal fertigation + 6g GO NP / 3L (per plot), on 15 & 45 DAS
T6	3000 ppm GO NP	Basal fertigation + 9g GO NP / 3L (per plot), on 15 & 45 DAS
T7	4000 ppm GO NP	Basal fertigation + 12g GO NP / 3L (per plot), on 15 & 45 DAS
T8	2000 ppm ZnO/GO NC	Basal fertigation + 6g NC/3L (per plot), on 15 & 45 DAS
T9	3000 ppm ZnO/GO NC	Basal fertigation + 9g NC / 3L (per plot), on 15 & 45 DAS
T10	4000 ppm ZnO/GO NC	Basal fertigation + 12g NC / 3L (per plot), on 15 & 45 DAS
T11	Standard ZnSO ₄ treatment	Basal fertigation + 9 g ZnSO ₄ ·7H ₂ O / 3L (per plot), on 15 & 45 DAS
T12	Vermicompost treatment	Basal fertigation + 1.8 kg (5 tonne/ha), applied before sowing

COH(M) 11 of maize (*Zea mays* L.) variety was purchased from Tamil Nadu Agricultural University (TNAU), Coimbatore, India. It was sown at a spacing of 25 × 60 cm. Figure 1 represent plotting area and field treatment placements of maize trials.

Crop Management

Standard agronomic practices for land preparation, irrigation, and pest management were followed throughout the season. All plots received basal NPK fertilizer according to the recommendations from TNAU and only the nano fertigation component differed among treatments. An overall plan for parameter measurements and scheduling is presented in Table 2.

Table 2
Experimental plan for sampling and data collection

Parameters	DAS	Measurements
Baseline Soil	Before sowing	pH, EC, C, N, P, K, S, Zn, Fe, Mn, Cu, MBC, DHA
Sowing	0	NA
Germination	8	% Germination (gap filling)
Vegetative growth 1	15	Plant height & number of leaves (fertigation 1)
Vegetative growth 2	30	Plant height & number of leaves
Vegetative growth 3	45	Plant height & number of leaves (fertigation 2)
Vegetative growth 4	60	Plant height & number of leaves
Tasseling	To be recorded	DAS
Silking	To be recorded	DAS
Reproductive growth	80	Plant height & number of leaves
Harvest	110	Plant height, number of leaves, cob length, biomass, 100-grain weight & yield
Post-harvest	114	pH, EC, C, N, P, K, S, Zn, Fe, Mn, Cu, MBC, DHA

Fertigation is carried out manually on 15 DAS and 45 DAS as per recommendations from TNAU. For basal manure, all plots received 67.5:62.5:25 kg/ha of N:P₂O₅:K₂O as initial fertigation. The required quantity per plot (24.3gN/52.8g urea, 22.5g P/141g Single Super Phosphate and 9g K/15g Muriate of Potash) were measured and spread on the plot evenly. It was mixed thoroughly with the top soil using a hand hoe. Treatment T1 is a no fertigation control. It didn't receive further fertilizers. For other treatments, (using nanofertilizers T2 - T10), required quantity is measured and mixed with water. They are dispersed evenly on 15 DAS and 45 DAS. 25 kg/ha of ZnSO₄ · 7H₂O was used in treatment T11, applied on 15 DAS and 45 DAS. Treatment T12 received 5 t/ha vermicompost (1.8kg/plot) before sowing along with basal fertilizers.

Germination, Growth and Phenological Measurements

2 seeds were sown together in a single spot. A plot thus had 40 seeds. Germination was noted at 8th DAS and gap filling were done on the same day to ensure uniform distribution of plants. Number of seedlings germinated per plot was recorded before removing the additional seedling to maintain the uniformity. Growth observations as per Table 2 were recorded. Five plants were selected randomly from each plot to record growth parameters. Phenological changes were noted down when approximately 50% of plants in a plot reached tasseling (days to tasseling) and silking (days to silking).

Post-Harvest Measurements

At physiological maturity, five representative plants from each plot were harvested to measure the cob length and biomass (above ground). Grains were removed from the cobs after pooling the replicates of a treatment

together. 100 grains were separated, dried partially and weighed to measure the grain quality after drying for overnight at 45°C hot air oven. Grain yield was measured from each plot and converted to yield per hectare.

Soil Biological and Fertility Assessments

Soil samples were collected at baseline and at harvest from each treatment to assess changes in soil fertility and microbial activity. DHA was determined using the TTC reduction method (Casida et al. 1964) and MBC was estimated using the chloroform fumigation-extraction method (Vance et al. 1987). Soil nutrient parameters were analyzed using standard procedures recommended for agricultural soils.

Statistical Analysis

One way analysis of variance (ANOVA) was performed on all raw data using IBM-SPSS. Statistically significant difference among treatments means were computed using post-hoc statistical test - Tukey's HSD (Honestly Significant Difference) at a significance level of $p < 0.05$. Graphs were prepared in OriginPro and results are presented as mean $\pm$ standard error.

Results

Germination of seedling

Number of seedlings emerged on 8th DAS was recorded and analysed statistically to eliminate any bias before the start of field trials. The germination percentage was calculated and is shown in Table 3.

Table 3 Mean germination percentage of <i>Zea mays</i> seedlings in each treatment		
Treatment		Germination percentage
No fertigation control	T1	89.17 ^a
ZnO nanoparticle treatment	T2	90.00 ^a
	T3	88.33 ^a
	T4	88.33 ^a
Graphene oxide nanoparticle treatment	T5	91.67 ^a
	T6	93.33 ^a
	T7	85.00 ^a
ZnO/GO bio nanocomposite treatment	T8	89.17 ^a
	T9	90.00 ^a
	T10	87.50 ^a
Standard ZnSO ₄ treatment	T11	85.83 ^a
Vermicompost treatment	T12	89.17 ^a

Same lowercase letter which follow the experimental value within a column are not significantly different ($p < 0.05$, Tukey's HSD).

From the table, it was observed that there is no significant difference across treatments as far as germination is concerned. All the plots had similar germination of seeds. There is no bias in allocation of plots for seeds as a uniform germination was observed across the treatments. Gap filling was performed at the end of 8 DAS to ensure uniform distribution of plants.

Growth Responses Across DAS

Plant heights were monitored from 15 DAS up until harvest. From the graph below in Fig. 2, it is evident that plant growth increased gradually from 15 days till they entered reproductive stage. Later, it slowly reached a plateau. Treatments T8 and T5 were conducive for growth as indicated by the taller plants, starting from 15 DAS onwards. Treatments T10 and T4 had much smaller plants compared to control T1. Table 4 represent the mean plant height at various stages for all treatments. The difference is significant as denoted by the alphabets in suffix (superscript) for all treatments at various stages.

Table 4
Mean plant height of all treatments at various stages.

Treatments	Mean height of plants (cm)					
	15 DAS	30 DAS	45 DAS	60 DAS	80 DAS	110 DAS
No fertigation control						
T1	14.75 ^a	40.76 ^{bc}	88.02 ^c	135.71 ^c	168.29 ^e	180.88 ^e
ZnO nanoparticle treatment						
T2	17.64 ^g	50.51 ^f	104.37 ^g	159.08 ^g	184.14 ^h	203.45 ^h
T3	16.75 ^e	48.54 ^e	102.57 ^g	155.27 ^f	178.60 ^g	195.55 ^g
T4	14.91 ^{ab}	39.43 ^b	84.06 ^b	125.89 ^b	150.15 ^b	158.46 ^b
Graphene oxide nanoparticle treatment						
T5	18.08 ^h	55.82 ^h	113.09 ^j	170.05 ⁱ	192.93 ^j	215.50 ⁱ
T6	17.13 ^f	51.81 ^{fg}	107.16 ^h	162.81 ^h	186.09 ^{hi}	204.03 ^h
T7	15.15 ^{bc}	41.55 ^a	91.23 ^d	133.41 ^c	154.39 ^c	165.25 ^c
ZnO - Graphene oxide nanoparticle treatment						
T8	18.73 ⁱ	57.83 ⁱ	118.87 ^k	173.23 ^j	198.66 ^k	220.34 ^j
T9	16.20 ^d	48.47 ^e	99.31 ^f	151.90 ^e	172.29 ^f	187.97 ^f
T10	14.56 ^a	37.52 ^a	79.18 ^a	119.98 ^a	145.68 ^a	150.62 ^a
Standard ZnSO ₄ treatment						
T11	15.49 ^c	45.51 ^d	94.57 ^e	144.45 ^d	165.91 ^d	178.36 ^d
Vermicompost treatment						
T12	17.74 ^{gh}	53.56 ^g	109.74 ⁱ	164.69 ^h	187.25 ⁱ	205.15 ^h

Alphabets as superscript suffix indicate statistical groupings. Same lowercase letter which follow the experimental value within a column are not significantly different ($p < 0.05$, Tukey's HSD). Lower alphabets denote lower heights and higher alphabets denote greater heights.

A combination of Zinc oxide and graphene oxide has resulted in a synergism and hence has improved plant health and overall growth. Nano formulation of zinc had showed better development when compared to the conventional ZnSO_4 treatment. Vermicompost treatment had similar observations as bio nanocomposite at 2000 ppm. Graphene addition is shown to increase the soil aggregation and stability. Across multiple days, number of leaves from five representative plants in a single plot was counted and tabulated after assessing the significance of differences in Table 5 and represented graphically in Fig. 3.

Table 5
Mean number of leaves per plant across multiple treatments in different plant age.

Treatments	Mean number of leaves per plant					
	15 DAS	30 DAS	45 DAS	60 DAS	80 DAS	110 DAS
No fertigation control						
T1	3.0 ^a	5.5 ^{ab}	7.5 ^{bc}	9.5 ^{bc}	12.4 ^b	12.6 ^{cd}
ZnO nanoparticle treatment						
T2	3.7 ^{cd}	6.6 ^{de}	8.6 ^{ef}	10.6 ^{ef}	12.7 ^b	12.6 ^{cd}
T3	3.3 ^b	6.3 ^{cde}	8.3 ^{de}	10.3 ^{de}	12.6 ^b	13.0 ^{de}
T4	3.0 ^a	5.4 ^{ab}	7.1 ^{ab}	9.1 ^{ab}	11.3 ^a	12.0 ^{bc}
Graphene oxide nanoparticle treatment						
T5	4.0 ^d	6.8 ^e	8.8 ^f	10.8 ^f	13.6 ^c	13.7 ^f
T6	3.6 ^{bc}	6.5 ^{de}	8.5 ^{ef}	10.5 ^{ef}	12.6 ^b	12.7 ^d
T7	3.0 ^a	5.4 ^{de}	7.2 ^{ab}	9.2 ^{ab}	11.5 ^a	11.3 ^a
ZnO - Graphene oxide nanoparticle treatment						
T8	4.0 ^d	6.8 ^e	8.8 ^f	10.8 ^f	13.7 ^c	13.7 ^f
T9	3.0 ^a	6.2 ^{cd}	8.3 ^{de}	10.3 ^{de}	12.3 ^b	12.0 ^{bc}
T10	4.0 ^a	5.2 ^{ab}	7.0 ^a	9.0 ^a	11.4 ^a	11.4 ^{ab}
Standard ZnSO_4 treatment						
T11	3.0 ^a	5.8 ^{bc}	7.8 ^{cd}	9.8 ^{cd}	12.2 ^b	12.4 ^{cd}
Vermicompost treatment						
T12	4.0 ^d	6.6 ^{de}	8.6 ^{ef}	10.6 ^{ef}	13.5 ^c	13.4 ^{ef}

Alphabets as superscript suffix indicate statistical groupings. Same lowercase letter which follow the experimental value within a column are not significantly different ($p < 0.05$, Tukey's HSD). Lower alphabets denote lesser leaves and higher alphabets denote more leaves.

In both parameters measured, T8 showed better growth compared to T1 (no fertigation control). The significance is more pronounced in plant height as T8 belonged to the subset (f - k) whereas the control belonged to the subset (a - e) throughout the season. Shunned growth was observed in T10 (subset a throughout), T4 (subset a - b) followed by T7 (subset a-c).

Days to Tasseling and Silking

Phenological observations showed that nanocomposite-treated plots reached tasseling and silking slightly earlier than the control and conventional treatments. Since Tukey's test established a significant difference in the number of days, ZnO - graphene oxide treatment at 2000 ppm can be considered as an appropriate treatment for improving the physiology of plant. Compared to non-fertigation control, treatments T4, T7 and T10 showed a delay in flowering. The DAS of tasseling and silking observed for standard ZnSO₄ treatment was the same as control. Vermicompost treatment resulted in an earlier flowering and is comparable to treatments T2, T5 and T8. Figure 4 shows tasseling and silking observed for maize crop at the end of 80 DAS.

Table 6
Phenological comparison of maize cultivation across treatments.

Treatment		Tasseling DAS	Silking DAS	Difference in days between tasseling and silking
No fertigation control	T1	66.3 ^{ab}	69.7 ^{abc}	3.4
ZnO nanoparticle treatment	T2	64.7 ^a	67.3 ^{ab}	2.6
	T3	65.3 ^a	68.3 ^{ab}	3.0
	T4	68.0 ^{ab}	72.3 ^{bc}	4.3
GO nanoparticle treatment	T5	64.3 ^a	67.3 ^{ab}	3.0
	T6	64.7 ^a	67.5 ^{ab}	2.8
	T7	66.7 ^{ab}	69.7 ^{abc}	3.0
ZnO/GO bio nanocomposite treatment	T8	64.3 ^a	68.0 ^{ab}	3.7
	T9	66.0 ^{ab}	69.0 ^{ab}	3.0
	T10	70.3 ^b	74.3 ^c	4.0
Standard ZnSO ₄ treatment	T11	67.0 ^{ab}	70.3 ^{abc}	3.3
Vermicompost treatment	T12	63.7 ^a	66.7 ^a	3.0

Alphabets as superscript suffix indicate statistical groupings. Same lowercase letter which follow the experimental value within a column are not significantly different ($p < 0.05$, Tukey's HSD). Lower alphabets denote lesser DAS and higher alphabets denote higher DAS.

Earlier tasseling and silking are associated with reduced stress during the reproductive window. Using Tukey's HSD, treatments T2, T5, T8, T12 showed higher or similar flowering as that of control. A delay of 1 or more days was significantly noted for T4 and T10 (higher NP & NC treatment). Stress induced delaying of flowering was noticed in those two cases.

Post-Harvest Characteristics

Post-harvest parameters measured include cob length (cm), biomass (kg), 100 grain weight (g) and yield (kg/plot). A compilation of all the parameters monitored is tabulated (Table 7).

Table 7
Post-harvest parameters (cob length, biomass above the ground, 100 grain weight and yield) of all treatments

Treatments	Post-harvest parameters					
	Cob length (cm)	Biomass (kg)	100 grain weight (g)	Yield (kg/plot)	Yield (kg/ha)	% Difference in yield
No fertigation control						
T1	18.2 ^c	1.26 ^c	25.17 ^d	2.48 ^c	6889 ^c	NA
ZnO nanoparticle treatment						
T2	20.0 ^f	1.65 ^f	28.67 ^{gh}	3.02 ^g	8389 ^g	21.8%
T3	19.5 ^e	1.50 ^e	27.50 ^f	2.81 ^e	7806 ^e	13.3%
T4	16.9 ^b	1.08 ^b	23.27 ^b	2.18 ^b	6056 ^b	-12.1%
Graphene oxide nanoparticle treatment						
T5	21.7 ^h	1.79 ^h	30.67 ⁱ	3.15 ^h	8750 ^h	27.0%
T6	20.0 ^f	1.62 ^f	28.33 ^{gh}	2.89 ^{ef}	8028 ^{ef}	16.5%
T7	17.8 ^f	1.12 ^b	24.00 ^c	2.22 ^b	6167 ^b	-10.5%
ZnO - Graphene oxide nanoparticle treatment						
T8	22.2 ⁱ	1.87 ⁱ	31.50 ^j	3.31 ^j	9194 ^j	33.5%
T9	19.2 ^{de}	1.47 ^e	26.97 ^f	2.67 ^d	7417 ^d	7.7%
T10	16.4 ^a	0.94 ^a	22.13 ^a	1.95 ^a	5417 ^a	-21.4%
Standard ZnSO ₄ treatment						
T11	18.8 ^d	1.35 ^d	26.13 ^e	2.48 ^c	7028 ^c	2.0%
Vermicompost treatment						
T12	21.0 ^g	1.72 ^g	29.10 ^h	2.93 ^{fg}	8139 ^{fg}	18.1%

Alphabets as superscript suffix indicate statistical groupings. Same lowercase letter which follow the experimental value within a column are not significantly different ($p < 0.05$, Tukey's HSD). Lower alphabets denote lesser value and higher alphabets denote higher value.

Cob length varied noticeably among treatments. Nanocomposite treatments and vermicompost treatment produced longer cobs than the control. Higher cob length is often an early indicator of improved pollination and grain set. Biomass at harvest also followed a similar pattern as we observed a comparatively improved biomass from plants in nanocomposite treatment plots recording. This suggests better nutrient conversion into structural and reproductive growth. The 100 grain weight showed improvement under nanocomposite fertigation. It can be concluded that nanocomposite based fertigation can improve kernel quality and nutritional content. Yield per hectare showed a tremendous increase of up to 33%, indicating that the

methodology can help in closing the yield gap between fertigation and harvest. Higher yield in nanocomposite treatment is attributed to the synergistic effect of ZnO and graphene oxide nanoparticles.

Soil Biological Activity and Fertility Changes

Soil measurements at harvest provided useful insight into how the nanocomposite interacted with the soil environment. Both DHA and MBC increased under nanocomposite treatments compared to the baseline and the control. The nanocomposite did not have any negative effect on the soil quality and microbial activity. It had contributed to the improvement of microbial biomass and enzyme activity as shown in Table 8 and 9.

Table 8
pH, electrical conductivity and macronutrient measurement of soil before and after harvest from all treatments.

Treatments	Lab measurements		Macronutrients				
	pH	EC	Carbon	Nitrogen	Potassium	Phosphate	Sulphur
Units	pH units	dS m ⁻¹	%C	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹
Before treatment							
-	7.60 (± 0.05)	0.32 (± 0.01)	0.40 (± 0.02)	245 (± 5)	18 (± 1)	280 (± 8)	16 (± 1)
No fertigation control							
T1	7.59 (± 0.04)	0.32 (± 0.01)	0.40 (± 0.02)	246 (± 6)	18 (± 1)	281 (± 8)	16 (± 1)
ZnO nanoparticle treatment							
T2	7.58 (± 0.04)	0.33 (± 0.01)	0.41 (± 0.02)	248 (± 6)	19 (± 1)	283 (± 8)	16 (± 1)
T3	7.56 (± 0.04)	0.34 (± 0.01)	0.42 (± 0.02)	250 (± 7)	19 (± 1)	285 (± 8)	17 (± 1)
T4	7.55 (± 0.04)	0.35 (± 0.01)	0.43 (± 0.02)	252 (± 7)	20 (± 1)	287 (± 8)	17 (± 1)
Graphene oxide nanoparticle treatment							
T5	7.54 (± 0.04)	0.34 (± 0.01)	0.46 (± 0.02)	255 (± 8)	21 (± 1)	290 (± 9)	18 (± 1)
T6	7.52 (± 0.04)	0.35 (± 0.01)	0.49 (± 0.02)	260 (± 8)	21 (± 1)	294 (± 9)	18 (± 1)
T7	7.50 (± 0.04)	0.36 (± 0.02)	0.52 (± 0.02)	265 (± 9)	22 (± 1)	298 (± 9)	19 (± 1)
ZnO - Graphene oxide nanoparticle treatment							
T8	7.50 (± 0.05)	0.36 (± 0.02)	0.50 (± 0.02)	270 (± 9)	22 (± 1)	300 (± 9)	19 (± 1)
T9	7.48 (± 0.05)	0.38 (± 0.02)	0.54 (± 0.02)	280 (± 10)	23 (± 1)	305 (± 10)	20 (± 1)
T10	7.46 (± 0.05)	0.40 (± 0.02)	0.58 (± 0.03)	290 (± 10)	24 (± 1)	310 (± 10)	20 (± 1)
Standard ZnSO ₄ treatment							
T11	7.57 (± 0.05)	0.34 (± 0.01)	0.42 (± 0.02)	255 (± 7)	19 (± 1)	285 (± 9)	17 (± 1)
Vermicompost treatment							
T12	7.45 (± 0.05)	0.39 (± 0.02)	0.65 (± 0.03)	300 (± 12)	25 (± 1)	320 (± 10)	21 (± 1)

Table 9

Micronutrient and biological activity measurement of soil before and after harvest from all treatments.

Treatments	Micronutrients				Biological activity	
	Zn	Cu	Mn	Fe	DHA	MBC
Units	ppm	ppm	ppm	ppm	$\mu\text{g TPF}$ $\text{g}^{-1} \text{h}^{-1}$	mg C kg^{-1}
Before treatment						
-	0.60 (± 0.05)	0.25 (± 0.02)	4.50 (± 0.30)	22.0 (± 1.0)	12.0 (± 1.0)	160 (± 12)
No fertigation control						
T1	0.60 (± 0.05)	0.25 (± 0.02)	4.50 (± 0.30)	22.5 (± 1.0)	12.5 (± 1.1)	165 (± 15)
ZnO nanoparticle treatment						
T2	0.90 (± 0.06)	0.26 (± 0.02)	4.60 (± 0.30)	22.8 (± 1.0)	13.0 (± 1.2)	175 (± 16)
T3	1.10 (± 0.07)	0.27 (± 0.02)	4.70 (± 0.30)	23.0 (± 1.1)	13.5 (± 1.3)	185 (± 17)
T4	1.30 (± 0.08)	0.28 (± 0.02)	4.80 (± 0.30)	23.2 (± 1.1)	14.0 (± 1.4)	195 (± 15)
Graphene oxide nanoparticle treatment						
T5	0.65 (± 0.05)	0.30 (± 0.02)	5.20 (± 0.40)	24.0 (± 1.2)	18.0 (± 2.0)	205 (± 24)
T6	0.68 (± 0.06)	0.32 (± 0.02)	5.60 (± 0.40)	25.0 (± 1.2)	22.0 (± 2.2)	220 (± 18)
T7	0.70 (± 0.06)	0.34 (± 0.02)	6.00 (± 0.50)	26.0 (± 1.3)	26.0 (± 2.5)	235 (± 22)
ZnO - Graphene oxide nanoparticle treatment						
T8	1.00 (± 0.08)	0.33 (± 0.02)	5.80 (± 0.50)	25.5 (± 1.3)	24.0 (± 2.3)	240 (± 25)
T9	1.30 (± 0.10)	0.36 (± 0.02)	6.20 (± 0.50)	26.5 (± 1.4)	28.0 (± 2.8)	260 (± 28)
T10	1.60 (± 0.12)	0.38 (± 0.02)	6.50 (± 0.50)	27.5 (± 1.4)	32.0 (± 3.0)	285 (± 18)
Standard ZnSO ₄ treatment						
T11	1.00 (± 0.08)	0.27 (± 0.02)	4.90 (± 0.40)	23.5 (± 1.2)	14.0 (± 1.4)	200 (± 20)
Vermicompost treatment						
T12	0.80 (± 0.07)	0.40 (± 0.03)	7.00 (± 0.60)	30.0 (± 1.5)	30.0 (± 3.0)	310 (± 16)

pH values remained slightly alkaline throughout the cultivation. It indicates that the treatments have not affected the soil quality. Electrical conductivity increase remained well within safe limits. Soil chemical balance was not negatively impacted due to nanocomposite treatments. Increase in carbon content was more prominently observed for vermicompost treatment compared to others. DHC and MBC indicators have provided a good tool for soil health improvements.

Discussion

The uniform germination observed across all plots indicated that the experimental plots were comparable at the initial establishment stage. Shew et al. (2022) reported that maize germination and early stand establishment are primarily influenced by seed vigour, soil moisture and temperature. The study also highlighted that nutrient treatments introduced after emergence do not affect germination outcomes. Zhao F et al. (2021) demonstrated that when fertilizers were applied after early seedling stages, germination

percentages would remain uniform across treatments. Variability were reported later in growth or physiological responses.

Zn is a critical micronutrient for maize as it influences chlorophyll production, photosynthesis, nutrient uptake, protein synthesis, and overall metabolism (Ariraman et al. 2020). It was noted that maize plants exhibited improved plant height, stem diameter, fresh and dry weight upon graphene application for soil conditioning. The reason was attributed to its higher surface area and adsorption capacity. Higher doses of graphene were found to inhibit nutrient delivery either due to root surface coating or excess graphene interference (Wang et al. 2023). Appearance of earlier phenological characteristics in 2000 ppm ZnO/GO NC was contributed by the availability of nutrients and improved plant health. It is well documented that a delay in silking is attributed to stress and nutritional imbalance (Salika and Riffat 2021). Hence the delay in tasselling and silking for treatments with higher concentration of ZnO and graphene oxide nanoparticle and ZnO/GO NC could be attributed to the nano toxicity exerted on the plants. Fertilizers when supplied in nano form helped the plants to overcome stress due to salinity in maize (Shoukat et al. 2024). Watering was done once in a week if there was no rainfall and seed coating of maize with nano ZnO at 40 ppm produced improved Cob girth, grains per cob, 100 grain weight, grain yield and biological yield of *Zea mays* compared to foliar or soil ZnSO₄ application in lateritic soils of West Bengal (Aktar et al. 2024). Many researchers have explored the use of graphene based nutrient delivery mode for bioactive molecules as it affects the soil retention properties (Bhattacharya et al. 2022). Higher concentrations of ZnO in wheat showed negative impacts in growth and yield parameters (Nazir et al. 2024).

To obtain an integrated view of treatment performance across all growth and post-harvest parameters, the Tukey HSD groupings were converted into numerical scores. Control group was assigned 0, positive scores indicated traits in which a treatment significantly outperformed the control, while negative scores reflected traits in which performance was significantly reduced, as shown in Table 10.

Table 10

Treatment wise scores calculated from Tukey's HSD groupings across all growth and yield parameters.

Treatment	Germination	Plant height (cm) on 110 DAS	Number of leaves on 110 DAS	Tasseling DAS	Silking DAS	Cob length (cm)	Biomass (kg)	100 grain weight (g)	yield (per plot)
T1	0	0	0	0	0	0	0	0	0
T2	0	3	0	0	0	3	4	5	4
T3	0	2	0	0	0	2	3	3	2
T4	0	-3	-1	1	1	-2	-1	-2	-1
T5	0	4	1	0	0	5	6	6	5
T6	0	3	0	0	0	3	4	4	3
T7	0	-2	-1	1	1	-1	-1	-1	-1
T8	0	5	1	0	0	6	7	7	6
T9	0	1	0	0	0	2	2	2	1
T10	0	-4	-1	1	1	-3	-2	-3	-2
T11	0	-1	0	0	0	1	1	1	0
T12	0	3	1	0	0	4	5	5	4

Summing these scores for each treatment enabled deriving a single composite index that captured the overall biological response across multiple dimensions of plant growth, phenological observations and yield. Overall sum of all parameters observed for each treatment was compared against control to understand the impact of each treatment. Figure 5 shows the plot of treatment wise comparison. This integration enabled the establishment of ranks among treatments.

It is visually understood that 2000 ppm of ZnO/GO NC (treatment 8) performed better than 2000 ppm of ZnO NP (treatment 5) followed by vermicompost (treatment 12). Standard zinc treatment (T11) had very minimal improvement in plant characteristics. Soil analyses after harvest from calcareous soils from Egypt showed improved nutrient availability. Nanoparticle based fertilizers helped to improve the product yield by circumventing limitations of alkaline soils (Sary and Abd El-Aziz 2025). Microbial population (bacteria, fungi and actinomycetes) and enzyme activities (dehydrogenase and acid phosphatase) were significantly higher in nano fertilizer treated soils compared to conventional fertilizer control (Khardi et al. 2023). An increase in chlorophyll and related photosynthetic pigment was reported with ZnO nano fertilizer treatment (Azam et al. 2022). There is a need for generation of more field based and long term data before adaptation of new methodologies. Ecotoxicological studies are recommended in several literatures for nano fertilizers (Hanif et al. 2024).

Conclusion

An effective field application of ZnO/GO NC in *Zea mays* for improvement of crop parameters was demonstrated. 2000 ppm of nanocomposite treatment has showed improved germination, plant vegetative growth, vitality, reproductive growth and yield parameters such as cob length, biomass, 100 grain weight and yield/hectare. There is a significant difference in all the parameters tested compared to no fertigation control as well as standard ZnSO₄ treatment. Vermicompost treatment had better yield, however statistical analysis indicated a more pronounced trend in nanocomposite treatment. The improved overall growth and productivity could be attributed to the nutrient availability and enrichment due to the synergistic effects of the two components in the nanocomposite. With increase in nanocomposite concentration, a decrease in all parameters were observed which could be attributed to the stress created by nanoparticles and nanocomposites. Soil chemical properties remained unchanged after the harvest. Apart from that, there was an improvement in biological activity indicating the soil rejuvenation potential of the treatment at 2000 ppm. This methodology could be adopted for maize cultivation to improve crop productivity and soil sustainability.

Declarations

Acknowledgements The authors are thankful to the extensive support by DBT-STAR (BT/HRD/11/09/2018), DBT-PG Scheme (BT/HRD/01/07/2020) and DST-FIST (SR/FST/College-235/2014) for financial and Instrumentation support. Moreover, the authors are grateful to Dr. R. Gopalakrishnan, Principal, K.S.Rangasamy College of Technology and Dr. B. Kalpana, Associate Professor and Head, Department of Biotechnology for their rendered support and the facilities to carry out this research work.

Author contribution

Data Availability

Data will be available upon request.

Conflict of interest The authors declare that they have no conflict of interest.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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Figures

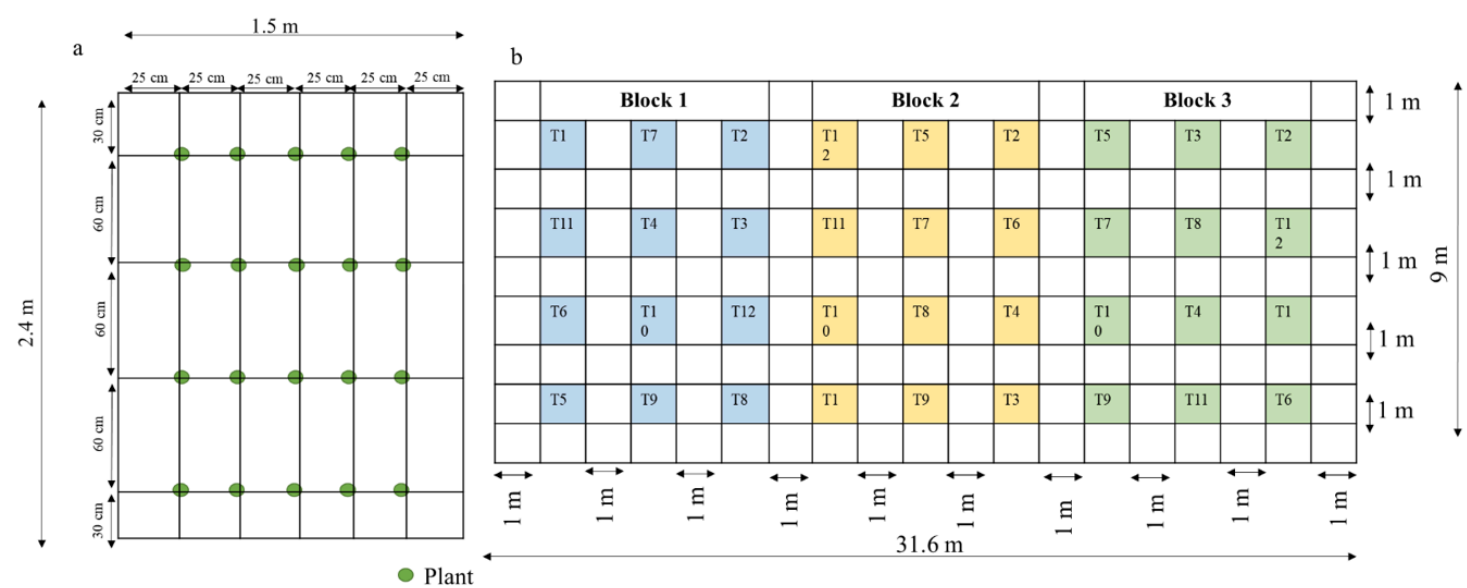


Figure 1

(a) Plot dimensions and (b) field dimension of the study; block 1, 2 and 3 represent the replicates of all the twelve treatments.

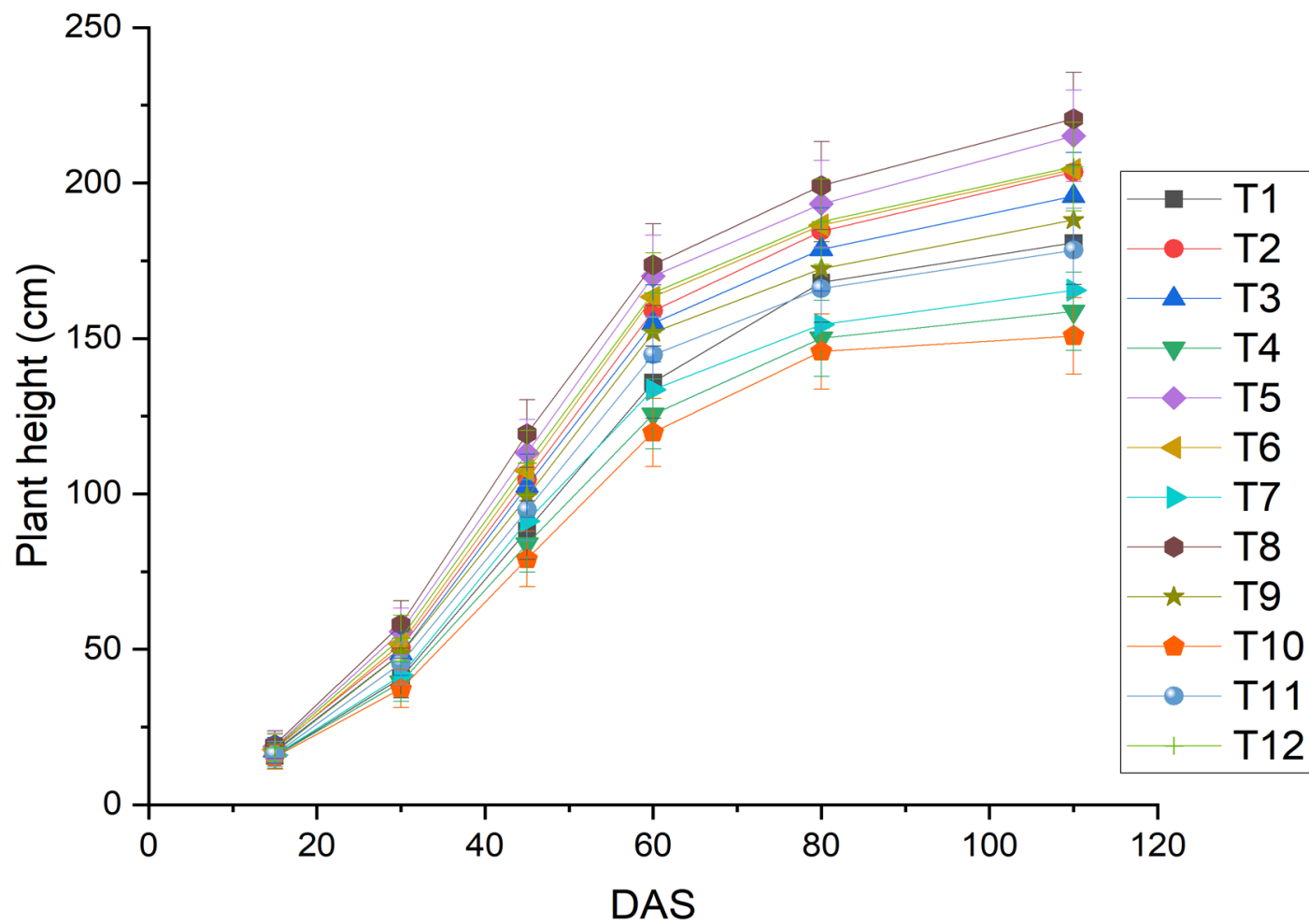


Figure 2

Plant height monitored for all treatments from sowing till harvest.

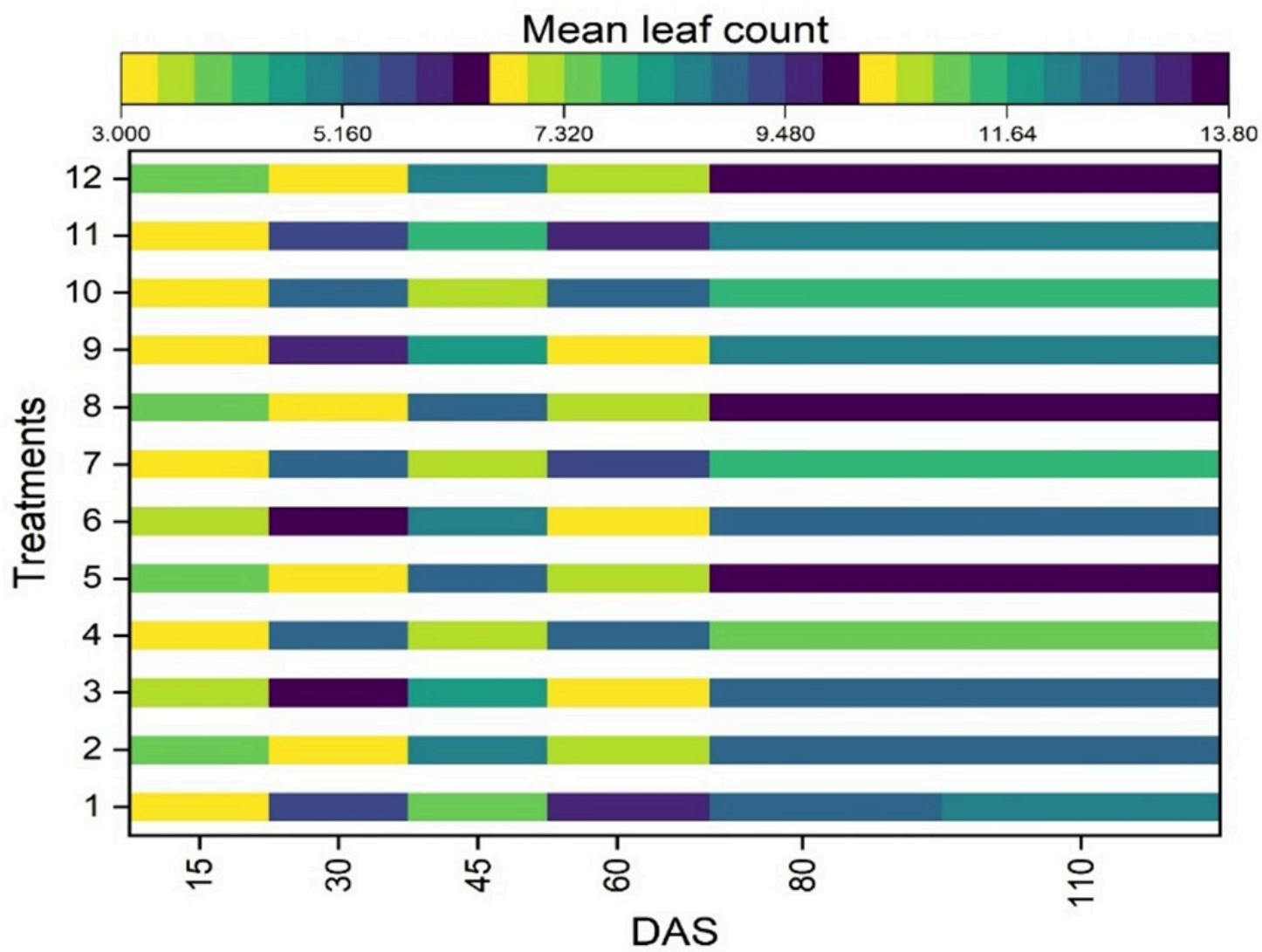


Figure 3

Number of leaves in maize cultivation across multiple treatments in various stages.

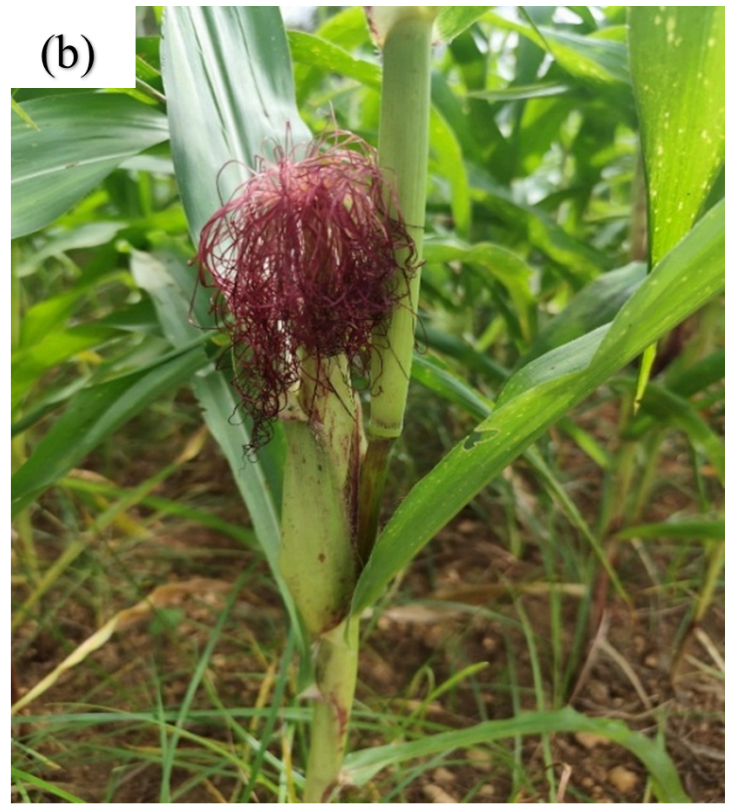


Figure 4

(a) Tasseling and (b) silking observed in *Zea mays* on 80 DAS

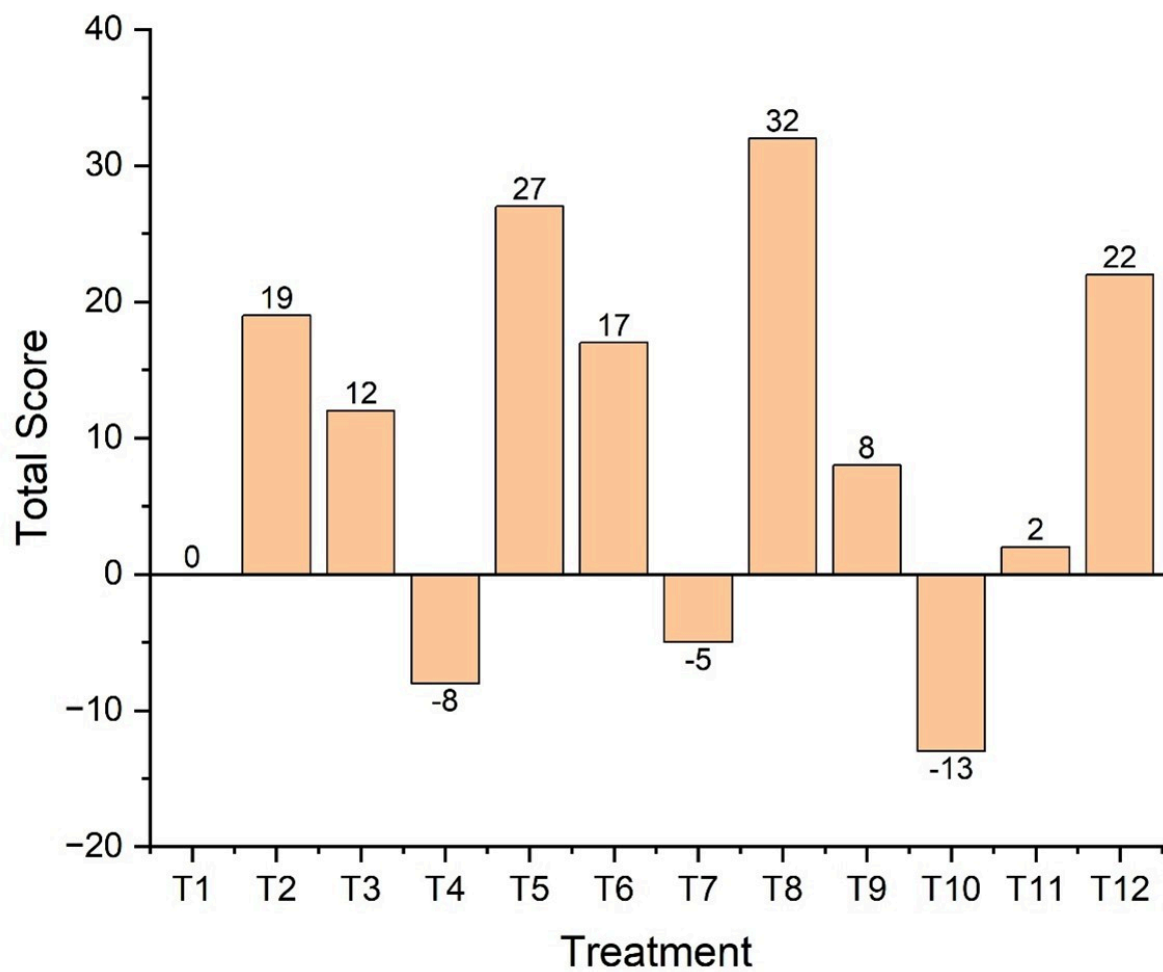


Figure 5

Total Performance Score of Treatments Across All Measured Parameters