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RESEARCH ARTICLE

Micronutrient-enriched organic amendments for maize cultivation in sodic soils: A multivariate analysis perspective

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Abstract

A field experiment was conducted at Tamil Nadu Agricultural University, Trichy, under the All India Coordinated Research Project (AICRP), to assess the effect of organic amendments and micronutrient enrichment on maize (*Zea mays* L.) performance in sodic soil. The study utilized vermicompost (VC) and farmyard manure (FYM) combined with an inorganic micronutrient mixture, applying eleven treatments in a Randomized Complete Block Design (RCBD) with three replications. Plant growth (height, leaf area, stem girth) and yield attributes (cob length, cob girth, kernel count, grain weight) were recorded and analyzed using Principal Component Analysis (PCA) to identify key influencing traits. The results demonstrated a significant improvement in maize growth and yield by applying a micronutrient mixture at 25 kg ha^{-1} enriched with VC (1:10) and zinc-solubilizing bacteria (ZSB). This treatment recorded the highest cob length (21 cm), girth (5.41 cm), kernels per cob (573.8 kernels/Cob) and grain weight (3.96 kg), highlighting the synergistic effect of organic amendments, micronutrient enrichment and microbial inoculation. PCA revealed that the first principal component (PC1) captured 96.88 % of the variance, primarily influenced by cob girth, grain weight, stem girth, leaf area and plant height. Biplot analysis effectively distinguished treatment effects, highlighting the efficacy of fortified vermicompost with ZSB. This study emphasizes the potential of integrating organic and inorganic inputs with PCA as a powerful tool for identifying key yield determinants in sodic soils, contributing to sustainable agricultural practices.

Keywords: growth; inorganic; maize; organic; PCA analysis; yield

Introduction

Soil fertility and crop productivity rely on the balanced availability of both macronutrients (N, P, K) and micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl, Ni), which are crucial for plant metabolism, enzyme activation and overall growth (1). Although micronutrients are required in trace amounts, their deficiency or imbalance can cause severe nutrient disorders such as chlorosis and stunted growth, ultimately, reducing yields and poor crop quality. Modern agricultural practices, including continuous monocropping, excessive chemical fertilizer use and declining organic matter, have significantly depleted soil micronutrients by promoting nutrient fixation, leaching and reduced microbial activity (2, 3). Among micronutrients, zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) play vital roles in plant physiological and biochemical functions. Copper (Cu) plays a crucial role in enzyme activity and functions as a catalyst in plant growth processes. It is involved in electron transport and lignin synthesis, contributing to overall plant health. Iron (Fe) is essential for nucleic acid synthesis, phytohormone synthesis and Fe-dependent enzymatic activities that regulate various metabolic functions. Manganese (Mn) is vital for photosynthesis, seed germination and enzymatic activities, particularly in redox reactions and oxidative stress management. Zinc (Zn) plays a fundamental role in multiple metabolic pathways, contributing to chlorophyll production, auxin synthesis and dehydrogenase enzyme activity, which influences plant growth and development. Globally, nearly half of the world's agricultural soils are zinc-deficient, particularly in calcareous and high-pH soils where Zn forms insoluble complexes with carbonates, reducing bioavailability (4, 5). This deficiency not only impacts crop productivity but also lowers grain nutritional quality, contributing to widespread malnutrition (6). Sodic soils contain excessive exchangeable sodium, leading to physical, chemical and biological challenges that hinder plant growth and soil health. Physically, these soils have poor aggregation and dispersion, resulting in surface crusting, low infiltration rates and hard-setting behavior that restricts root penetration. High bulk density further limits aeration and root development. Chemically, sodic soils exhibit a high Exchangeable Sodium Percentage (ESP > 15 %) and elevated pH levels (> 8.5 to 10.5), which disrupt nutrient availability and create imbalances in essential elements like calcium, magnesium, potassium, zinc, iron, manganese, copper and phosphorus. Additionally, sodium and chloride accumulation, along with a high Sodium Adsorption Ratio (SAR), impairs soil permeability and exacerbates water stress. Biologically, sodic conditions reduce microbial diversity and activity, slowing organic matter decomposition and nutrient cycling, further diminishing soil fertility. Despite advancements in sodic soil remediation, certain research gaps persist. Most studies emphasize chemical amendments like gypsum, while sustainable options such as biofortified vermicompost, biochar and microbial inoculants remain underexplored. Additionally, organic amendments and micronutrients are often examined separately rather than as a combined strategy for enhancing maize growth in sodic soils. The application of Principal Component Analysis (PCA) in assessing soil fertility and crop responses is also limited, despite its ability to identify critical factors affecting productivity. To bridge these gaps, this study will assess the impact of organic amendments and micronutrient mixtures on maize growth in sodic soil, focusing on changes in soil properties, microbial activity and nutrient availability. By utilizing PCA, key soil and plant parameters will be identified, contributing to the development of an optimized organic and micronutrient-based amendment approach for improving maize yield and soil health in sodic environments. Biofortified vermicompost, enriched with micronutrients and zinc-solubilizing bacteria (ZSB), has emerged as a sustainable strategy for enhancing soil fertility by increasing Zn bioavailability through organic acid production and microbial activity (7, 8). Vermicomposting, mediated by earthworms and microbes, improves soil fertility by enhancing microbial diversity and increasing nutrient solubilization and releasing natural chelators like humic and amino acids, which enhance micronutrient bioavailability (9). Integrated approach of combining micronutrient-enriched vermicompost, farmyard manure (FYM) and ZSB bio-inoculants has shown promise in optimizes soil nutrient dynamics, enhances zinc use efficiency (ZUE) by solubilizing unavailable Zn forms and reduces reliance on synthetic fertilizers (10). This study evaluates the combined effects of micronutrient-enriched vermicompost, FYM and ZSB on maize (*Zea mays* L.) performance in sodic soils, with the goal of developing sustainable and cost-effective strategies to mitigate sodicity stress, enhance soil fertility and improve agricultural productivity in degraded soils.

Materials and Methods

Experimental location

The ESP threshold for sodicity is typically 15%. Soils with an ESP > 15% are classified as sodic soils due to structural degradation, poor water infiltration and reduced nutrient availability. The field experiment on maize was conducted in sodic soil at the Eastern Block of the All India Coordinated Research Project (AICRP), Department of Soil Science, TNAU, Trichy. This site is situated within the Cauvery Delta Zone of Tamil Nadu, positioned at 10.8°N latitude and 79°E longitude, with an elevation of 428.7 m above mean sea level (MSL).

Experimental inputs

Organic wastes such as farmyard manure (FYM) and vermicompost (VC) were collected from the Central Farm, Department of Agronomy, TNAU, Trichy. The organic manure samples were taken to the laboratory, air-dried in the shade, ground and passed through a 2.0 mm sieve to ensure homogenization. The samples were then preserved for detailed analysis. The standard methods used for analyzing organic manure samples are outlined in experimental analysis.

Experimental analysis

The experimental analysis involved evaluating the physical, physicochemical and chemical properties of the soil and fortified organic mixtures used in the study. The standard methods used for analyzing organic manure samples are outlined here. Moisture content was determined using the gravimetric method by oven-drying samples at 105 °C, as per the standard procedure outlined by (11). Physicochemical parameters, including soil reaction (pH) and electrical conductivity (EC), were measured using a potentiometric pH meter and a conductometric EC meter, respectively, with a soil-to-water ratio of 1:5, following the methodology described (12). Cation exchange capacity (CEC) was estimated using neutral normal ammonium acetate (NH_4OAc), following procedure (12). The chemical properties of the soil were analyzed to determine organic carbon, total nitrogen, phosphorus, potassium, calcium and magnesium content. Organic carbon was quantified using the chromic acid wet digestion method was followed (13). Total nitrogen was estimated using the modified Kjeldahl method (14), while total phosphorus was extracted using a triple acid mixture (HNO_3:H_2SO_4:$HClO_4$ in a 9:2:1 ratio) and determined by the vanadomolybdate method (14) Total potassium was extracted using the same triple acid mixture, neutralized with ammonia and measured using a flame photometer was followed (15). The total calcium and magnesium contents were determined using the Versenate method after triple acid extraction (12). Additionally, the availability of micronutrients, including zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu), was assessed using the DTPA extraction method with 0.005 M DTPA, followed by analysis with an Atomic Absorption Spectrophotometer (AAS), based on the procedure established (16). These analytical methods provided a comprehensive assessment of the soil and fortified organic mixtures, ensuring an accurate understanding of their nutrient composition and availability.

Experimental design and treatment details

The field experiment was conducted in the north-western block of TNAU, Trichy, on sodic soil classified as Typic Natrustalfs. Maize Hybrid COH (M) 6 was selected as the test crop and the study was carried out during the *kharif* season. The experiment followed a Randomized Complete Block Design (RCBD) with eleven treatments with three replications. The plots sizes were 5 × 4 m, with a plant spacing of 25 × 60 cm.

The treatments comprised a control and various combinations of micronutrient mixtures and organic amendments. The control treatment (T_1) included vermicompost (VC) alone. Treatment T_2 involved the application of a micronutrient (MN) mixture at 25 kg ha^{-1}. In T_3, the MN mixture was enriched with farmyard manure (FYM) in a 1:10 ratio. Treatments T_4 to T_7 incorporated the MN mixture at 25 kg ha^{-1} with vermicompost (VC) enriched at different ratios, specifically 1:10 (T_4), 1:7.5 (T_5), 1:5 (T_6) and 1:2.5 (T_7). Further treatments included bio-inoculants in addition to VC-enriched MN mixtures. Treatment T_8 involved the application of MN mixture at 25 kg ha^{-1} with VC (1:10) and ZSB as a bio-inoculant. Similarly, T_9, T_{10} and T_{11} followed the same pattern, incorporating VC enrichment at 1:7.5, 1:5 and 1:2.5 ratios, respectively, along with ZSB. ZSB play a vital role in enhancing Zn availability in sodic soils through multiple mechanisms. They produce organic acids, such as citric, gluconic and oxalic acids, which help dissolve zinc from its insoluble forms (ZnO and $ZnCO_3$) by reducing the soil pH. Additionally, ZSB release siderophores, which bind to Zn and enhance its bioavailability for plant absorption. Their enzymatic activity further transforms unavailable Zn into forms that plants can easily absorb. Furthermore, the secretion of organic acids by these bacteria helps neutralize soil alkalinity, thereby improving Zn solubility and overall nutrient accessibility in sodic conditions. The bio-inoculant application rate was standardized, with 10 mL of ZSB added per kilogram of VC as outlined in Table 1. This experimental setup aimed to assess the effectiveness of fortified organic amendments and bio-inoculants in improving soil fertility and maize productivity in sodic soils.

Table 1. Treatments and their particulars

Treatments	Particulars
T_1	Vermicompost Alone (Control)
T_2	MN mix at 25kg ha^{-1}
T_3	MN mix at 25 kg ha^{-1} as enriched FYM (1:10) ratio
T_4	MN mix at 25 kg ha^{-1} as enriched VC (1:10) ratio
T_5	MN mix at 25 kg ha^{-1} as enriched VC (1:7.5) ratio
T_6	MN mix at 25 kg ha^{-1} as enriched VC (1:5) ratio
T_7	MN mix at 25 kg ha^{-1} as enriched VC (1:2.5) ratio
T_8	MN mix at 25 kg ha^{-1} as enriched VC (1:10) ratio + ZSB (BI)
T_9	MN mix at 25 kg ha^{-1} as enriched VC (1:7.5) ratio + ZSB (BI)
T_{10}	MN mix at 25 kg ha^{-1} as enriched VC (1:5) ratio + ZSB (BI)
T_{11}	MN mix at 25 kg ha^{-1} as enriched VC (1:2.5) ratio + ZSB (BI)

*MN - Micronutrient mixture; VC - Vermicompost; BI - Bio-inoculants; ZSB (BI) - For 1 kg VC = 10 mL BI to be added.

Preparation of micronutrient fertilizer mixture

Straight chemical fertilizers were physically mixed to create the micronutrient fertilizer mixture that was utilized for the enrichment technique. Table 2 outlines the mixture's chemical composition.

Fortification of organic manures with micronutrient mixtures and ZSB bio-inoculants

The enrichment of vermicompost and farmyard manure (FYM) with a micronutrient mixture and ZSB at different ratios enhances soil fertility and nutrient availability. The process begins by selecting well-decomposed, sieved vermicompost and FYM and preparing a micronutrient mixture specifically formulated for the maize crop. The enrichment treatments include FYM enriched with a micronutrient mixture at a 1:10 ratio, vermicompost enriched with a micronutrient mixture at ratios of 1:10, 1:7.5, 1:5 and 1:2.5 and vermicompost enriched with a micronutrient mixture along with ZSB at the same specific ratios of 1:10, 1:7.5, 1:5 and 1:2.5 was shown in Fig. 1. The ZSB bacterial strain, *Pseudomonas chlororaphis*, is cultured in a nutrient broth with molasses to achieve an optimal population density. The bacterial inoculum is then diluted and uniformly applied to the vermicompost, maintaining the appropriate moisture level (33.3 %) for VC and (50 %) for FYM. The mixture is sealed in polyethylene bags and incubated at room temperature for 30 days, with regular stirring to release CO_2 and support microbial activity. Moisture levels are consistently monitored and adjusted as needed. Once the enrichment process is complete, the enriched manure is stored in aerated bags for further analysis and potential field application.

Data collection

For sampling and data collection, five plants were randomly selected from the two middle rows of each plot. Observations were recorded for vegetative growth parameters, including number of leaves, leaf area, stem girth and plant height. Additionally, yield attributes such as cob length, girth, No. of kernels/cob, No. of rows/cob, No. of kernels/row and grain weight, were measured at crop maturity and harvest.

Statistical analysis

The data collected from the experimental field were analyzed using Analysis of Variance (ANOVA) with the Statistical Package for Social Sciences (17) for homogeneity of variances. To compare significant differences among treatments, Duncan's Multiple Range Test (DMRT) was employed at a 5 % probability level.

Table 2. Composition of maize micronutrient mixture

Salt	Symbol	Weight (Kg/100 kg)	Nutrient content (%)
Iron sulphate	$FeSO_4$	28.95	5.50
Manganese sulphate	$MnSO_4$	03.28	1.00
Zinc sulphate	$ZnSO_4$	26.19	5.50
Copper sulphate	$CuSO_4$	04.17	1.00
Borax	$Na_2B_4O_7{\cdot}10H_2O$	14.29	1.50
Sodium molybdate	$Na_2MoO_4{\cdot}2H_2O$	00.14	0.05
Magnesium sulphate	$MgSO_4$	05.20	0.50
Filler (Gypsum)	$CaSO_4{\cdot}2H_2O$	17.79	-
Total		**100.00**	-

Fig. 1. Different fortified organic mixtures were used in this study.

Results and Discussion

Characterization of experiment inputs

The chemical composition of vermicompost (VC) and farmyard manure (FYM) reveals significant differences in their nutrient profiles, organic matter content and CEC, all of which play a vital role in soil fertility and plant growth as highlighted in Table 3. Vermicompost exhibited a higher moisture content (11.20 %) compared to FYM (3.30 %), which may enhance microbial activity and nutrient mineralization. Both organic amendments maintained approximately neutral pH (7.34 for VC and 7.17 for FYM), contributing to soil pH stability. However, VC had a lower electrical conductivity (1.95 dS m^{-1}) than FYM (2.84 dS m^{-1}), suggesting reduced salt accumulation. In terms of nutrient retention, vermicompost demonstrated a significantly higher CEC (219 C mol/kg) than FYM (55 C mol/kg), indicating superior nutrient-holding capacity. It also contained nearly double the organic carbon content (16.91 %) compared to FYM (8.81 %), which supports soil structure and microbial diversity. Additionally, vermicompost was richer in total nitrogen (1.28 %) and total phosphorus (0.85 %) than FYM (1.05 % TN and 0.27 % TP), whereas FYM had a slightly higher total potassium content (0.37 %) compared to VC (0.34 %). For secondary nutrients, vermicompost contained higher levels of calcium (1.26 %) and magnesium (0.93 %) than FYM (0.96 % Ca and 0.37 % Mg), which can enhance soil structure and plant nutrient uptake. Regarding micronutrient composition, vermicompost was a better source of iron (320 mg/kg) and zinc (93.0 mg/kg), while FYM had higher concentrations of manganese (28.0 mg/kg) and copper (74.3 mg/kg), reflecting differences in their

Table 3. Chemical analysis of organic manures and inorganic sources used

Parameters	Organic manures	
	Vermicompost	FYM
Moisture (%)	11.20	3.30
pH	7.34	7.17
EC (dS m^{-1})	1.95	2.84
CEC Cmol (p^+) kg^{-1}	219	55
OC (%)	16.91	8.81
Total N (%)	1.28	1.05
Total P (%)	0.85	0.27
Total K (%)	0.34	0.31
Total Ca (%)	1.26	0.96
Total Mg (%)	0.93	0.37
Available Fe (mg kg^{-1})	320	283
Available Mn (mg kg^{-1})	12.0	28.0
Available Zn (mg kg^{-1})	93.0	80.0
Available Cu (mg kg^{-1})	62.4	74.3

micronutrient contributions. These results suggest that vermicompost is particularly beneficial for improving organic carbon, nitrogen, phosphorus, calcium, magnesium and zinc availability, whereas FYM provides a better supply of potassium, manganese and copper. The combined application of both organic amendments can help maintain a balanced nutrient supply, promoting soil health and enhancing plant productivity in sustainable agricultural systems.

Physiochemical characteristics of experimental soil

The physicochemical properties of the experimental soil provide valuable insights into its fertility status and suitability for crop cultivation (Table 4). The soil exhibits an alkaline pH of (8.8), indicative of its sodic, which may restrict the availability of essential micronutrients. However, the electrical conductivity (EC) of 0.27 dS m^{-1} confirms that the soil is non-saline and conducive to plant growth. The organic carbon (OC) content is measured at 0.53 %, falling within the low to medium range, which may limit microbial activity and nutrient retention. Additionally, the ESP of 18 suggests moderate sodicity, potentially affecting soil structure and water infiltration. Regarding macronutrient availability, the soil has a low nitrogen content (227 kg ha^{-1}), indicating the need for nitrogen supplementation. Phosphorus levels (20.1 kg ha^{-1}) are moderate. The increase in available phosphorus in soil through the application of micronutrients combined with organic treatments was previously reported (18, 19). While potassium (250 kg ha^{-1}) is present in sufficient amounts to support crop growth. Micronutrient analysis reveals that iron (4.71 mg kg^{-1}) and manganese (3.82 mg^{-1} kg) are near critical levels, while zinc (0.51 mg kg^{-1}) falls below the threshold, signifying a deficiency risk. Conversely, copper (1.81 mg^{-1}kg) is found to be adequate. Exchangeable calcium (16.9 Cmol (p^+) kg^{-1}) and magnesium (10.5 Cmol (p^+) k^{-1}g) are available in sufficient quantities, although high calcium levels may contribute to phosphorus fixation, reducing its availability to plants.

Table 4. Physiochemical characteristics of experimental soil

S.No	Constituents	Values
1	pH	8.8
2	EC (dS m^{-1})	0.27
3	OC (%)	0.53
4	ESP	18
5	Available N (kg ha^{-1})	227
6	Available P (kg ha^{-1})	20.1
7	Available K (kg ha^{-1})	250
8	DTPA-Fe (mg kg^{-1})	4.71
9	DTPA-Mn (mg kg^{-1})	3.82
10	DTPA - Zn (mg kg^{-1})	0.51
11	DTPA - Cu (mg kg^{-1})	1.81
12	Exchangeable Ca (C mol (p^+) kg^{-1})	16.9
13	Exchangeable Mg (C mol (p^+) kg^{-1})	10.5

To improve soil fertility and productivity, strategic management practices should be implemented. Incorporating organic amendments such as vermicompost and green manure enhances organic carbon, promotes microbial activity and improves nutrient cycling. The increase in the organic carbon content of post-harvest soil following the application of various micronutrient-fortified organic manure treatments in oilseed crops (20-22). A similar effect was observed in sesame crops (23). Zinc deficiency can be addressed through the application of zinc fertilizers or biofortified organic inputs. Micronutrient-fortified organic manures, particularly those enriched with Zn and Mn, can improve soil structure, enhance microbial activity and increase soil nitrogen availability by promoting nitrogen-fixing bacteria (24). The enhanced zinc availability could be attributed to the direct addition of nutrients through fertilizers and enriched organic manures, which help maintain higher levels of available zinc and other micronutrients in post-harvest soil. Additionally, the complexation of micronutrients with applied organic amendments may have mobilized and increased zinc availability in the soil. These findings align with the studies (24-26).

Effect of organic manures and inorganic sources on vegetative growth parameters of maize

The incorporation of micronutrient (MN) mixtures enriched with vermicompost (VC) and bio-inoculants had a significant impact on the vegetative growth parameters of maize, including plant height, number of leaves, leaf area and stem girth as illustrated in Table 5. The tallest plants were observed in treatment T_8 (MN mix at 25 kg ha^{-1} with enriched VC at a 1:10 ratio + ZSB, reaching 228 cm, followed by T_9 (225 cm) and T_{10} (221 cm). This suggests that the presence of ZSB played a crucial role in enhancing nutrient availability and promoting vegetative growth. In contrast, the control (T_1), which received only vermicompost, recorded the shortest plants at 181 cm, emphasizing the necessity of micronutrient enrichment for optimal growth. A similar pattern was observed in leaf count,

Table 5. Effect of organic manures and inorganic sources on vegetative growth parameters of hybrid maize

Treatments	Plant height (cm)	Number of leaves/plant	Leaves area (cm²)	Stem girth (cm)
T_1	181^{g}	10.00^{h}	431.39^{g}	11.62^{i}
T_2	184^{g}	11.03^{g}	470.58^{f}	12.56^{h}
T_3	190^{fg}	11.2^{g}	488.52^{ef}	12.87^{gh}
T_4	215^{bc}	12.7^{d}	527.34^{cd}	15.39^{cd}
T_5	210^{cd}	12.4^{de}	519.49^{d}	14.76^{de}
T_6	204^{de}	12.00^{ef}	507.96^{de}	14.13^{ef}
T_7	197^{ef}	11.6^{fg}	503.39^{de}	13.50^{fg}
T_8	228^{a}	15^{a}	615.60^{a}	17.90^{a}
T_9	225^{ab}	14.2^{b}	599.35^{ab}	17.27^{ab}
T_{10}	221^{abc}	14.00^{bc}	577.90^{b}	16.96^{b}
T_{11}	219^{abc}	13.5^{c}	549.73^{c}	16.01^{c}
SE(d)	4.936	0.273	11.494	0.37
CD(P = 0.05)	10	0.569	23.975	0.773

where T_8 recorded the highest number of leaves (15), followed by T_9 (14.2) and T_{10} (14.0), highlighting the role of bio-inoculants in improving nutrient uptake and metabolic activity. The lowest number of leaves (10) was found in the control treatment (T_1), indicating that vermicompost alone was less effective in promoting leaf development. Leaf area was also significantly influenced by the treatments, with the highest value recorded in T_8 (615.60 cm^2), followed by T_9 (599.35 cm^2) and T_{10} (577.90 cm^2). This suggests that micronutrient enrichment, in combination with ZSB, enhanced photosynthetic efficiency and biomass accumulation. Conversely, the lowest leaf area (431.39 cm^2) was recorded in T_1, demonstrating the limited effect of unfortified vermicompost in stimulating vegetative growth. Stem girth, an indicator of plant robustness and structural strength, was also highest in T_8 (17.90 cm), followed by T_9 (17.27 cm) and T_{10} (16.96 cm), reflecting improved nutrient absorption, structural integrity and resistance to lodging. The lowest stem girth (11.62 cm) was observed in T_1, further reinforcing the importance of micronutrient enrichment and microbial inoculation for enhanced plant vigor.

The findings indicate that the application of micronutrient (MN) mixtures enriched with vermicompost (VC), particularly when supplemented with ZSB, significantly enhanced the vegetative growth of maize. However, micronutrient interactions in soil can sometimes exhibit antagonistic effects, where an excess of one nutrient impairs the uptake or utilization of another. A notable example is the high concentration of zinc (Zn), which can restrict phosphorus (P) uptake due to competition at the root level. Elevated Zn levels in the soil affect P availability through two primary mechanisms. First, excess Zn promotes the formation of insoluble Zn-phosphate complexes, reducing the amount of P accessible to plants through precipitation and fixation. Second, Zn and P compete for root transport sites and high Zn concentrations interfere with P absorption by altering root membrane permeability and transporter efficiency. The excessive Zn application in maize led to a decline in P content within plant tissues, reinforcing this antagonistic interaction research was demonstrated (27). Meanwhile, the incorporation of VC improves soil organic matter (SOM) by increasing soil organic carbon (SOC), stimulating microbial activity and promoting the formation of stable humic compounds. Its long-term benefits include enhanced nutrient retention, gradual nutrient release and improved soil structure. Over time, VC contributes to soil fertility, moisture retention and microbial diversity, making it an environmentally sustainable soil amendment. Among the treatments, T_8 (MN mix at 25 kg ha^{-1} as enriched VC (1:10) + ZSB) demonstrated the best performance, followed by T_9 and T_{10}. The enhanced nutrient availability increased microbial activity and improved soil conditions contributed to superior plant growth in these treatments. In contrast, the control (T_1) consistently recorded the lowest values across all parameters, confirming that vermicompost alone does not provide sufficient nutrients for optimal maize growth. The standard error of difference (SE(d)) and critical difference (CD) values at P = 0.05 demonstrate the statistical differences among treatments. These results underscore the potential benefits of integrating organic amendments with bio-inoculants to enhance crop productivity in sustainable agricultural systems. This aligns with the earlier findings was reported (28-30).

Effect of organic manures and inorganic sources on yield attributes of maize

The highest cob length (21 cm) was recorded in treatment T_8 (MN mix at 25 kg ha^{-1} with enriched VC at a 1:10 ratio + ZSB), followed closely by T_9 (19.2 cm) and T_{10} (19 cm). In contrast, the shortest cob length (15 cm) was observed in the control treatment (T_1), which received only vermicompost, indicating that combining organic amendments with ZSB significantly enhanced cob development. A similar trend was noted for cob girth, where T8 recorded the largest girth (5.41 cm), followed by T_9 (5.19 cm) and T_{10} (5.02 cm), while the smallest girth (3.54 cm) was found in T_1. This demonstrates that enriching vermicompost with a micronutrient mixture and bio-inoculants positively influenced cob size. The highest number of kernel rows per cob (15.1) was also observed in T_8, with T_9 (14.4) and T_{10} (14.0) following closely behind. The lowest row count (10.73) was recorded in T_1, highlighting the beneficial impact of micronutrient-enriched vermicompost and ZSB on kernel row formation. Similarly, the number of kernels per row was highest in T_8 (38), followed by T_9 (37.7) and T_{10} (36.4), whereas the lowest kernel count (29.4) was noted in T_1. This reinforces the role of organic amendments and ZSB in improving kernel setting and development. In terms of total kernel count per cob, T_{11} recorded the highest value (575.76), followed by T_8 (573.8) and T_9 (542.36), while T_1 had the lowest count (382.2). This suggests that vermicompost alone is less effective in improving kernel production compared to enriched VC with bio -inoculants.

The highest 100-grain weight (28 g) was observed in T_8, with T_9 (27.5 g) and T_{10} (27.3 g) showing slightly lower values. Meanwhile, the lowest 100-grain weight (22.1 g) was recorded in T_1, confirming that a combination of organic and inorganic amendments significantly enhances grain filling and weight. Regarding total grain weight, T_8 again recorded the highest value (3.96 kg), followed closely by T_9 (3.94 kg) and T_{10} (3.81 kg), whereas the lowest grain weight (3 kg) was observed in T_1. The critical difference (CD) values at P = 0.05 and the standard error of difference (SE(d)) possess statistical differences between treatments, which confirms that enriched VC combined with bio-inoculants substantially improves maize grain yield as depicted in Table 6. The results indicate that the application of a micronutrient mix at 25 kg ha^{-1} enriched with VC (1:10) and supplemented with ZSB (T_8) resulted in the best performance across all yield attributes. Treatments incorporating enriched vermicompost and bio-inoculants significantly improved maize growth and productivity compared to vermicompost alone. The higher yield observed in treatments with enriched organic manures can be attributed to the gradual release of micronutrients which supports enzymatic functions, nutrient recycling and auxin bio-synthesis-critical for root development and cell elongation (31). Additionally, these micronutrients, such as Zn and Mn enhance carbohydrate metabolism and promote efficient translocation of assimilates to develop kernels, improving seed formation and grain filling (25). These findings highlight the importance of integrating organic and inorganic nutrient sources, particularly enriched vermicompost with bio-inoculants, to enhance nutrient availability and optimize maize yield in sustainable farming systems.

Table 6. Effect of organic manures and inorganic sources on yield attributes of hybrid maize

Treatments	Cob length (Cm)	Cob girth (Cm)	No of rows cob^{-1}	No of kernels row^{-1}	No of kernels cob^{-1}	100-grain wt (Kg)	Grain weight (Kg)
T_1	15^{h}	3.54^{g}	10.73^{f}	29.4^{g}	382.2^{e}	22.1^{g}	3^{g}
T_2	16.2^{g}	3.84^{f}	11.05^{f}	31.1^{f}	410.52^{e}	23.3^{f}	3.18^{f}
T_3	16.6^{fg}	4.00^{ef}	11.13^{f}	33^{e}	447.8^{d}	25.6^{e}	3.27^{ef}
T_4	18^{de}	4.63^{d}	13.1^{d}	35.9^{bc}	527.73^{bc}	27.0^{abcd}	3.63^{c}
T_5	17.9^{de}	4.51^{d}	12.70^{d}	35.7^{bcd}	507.25^{c}	26.8^{bcd}	3.57^{cd}
T_6	17.6^{de}	4.45^{d}	12.05^{e}	35.1^{cd}	475.17^{d}	26.4^{cde}	3.43^{de}
T_7	17.2^{ef}	4.18^{e}	11.86^{e}	34.5^{d}	460.4^{d}	26^{de}	3.35^{e}
T_8	21^{a}	5.41^{a}	15.1^{a}	38^{a}	573.8^{a}	28^{a}	3.96^{a}
T_9	19.2^{b}	5.19^{b}	14.4^{b}	37.7^{a}	542.36^{a}	27.5^{ab}	3.94^{a}
T_{10}	19^{bc}	5.02^{bc}	14.00^{bc}	36.4^{b}	534.28^{b}	27.3^{abc}	3.81^{ab}
T_{11}	18.2^{cd}	4.87^{c}	13.7^{c}	36.1^{bc}	575.76^{bc}	27.1^{abc}	3.73^{bc}
SE(d)	0.391	0.088	0.261	0.608	14.096	0.493	0.082
CD(P = 0.05)	0.816	0.183	0.545	1.269	29.405	1.029	0.171

Agronomic Efficiency (AE) and Partial Factor Productivity (PFP) in maize cultivation

The application of different treatments incorporating micronutrient mixtures, vermicompost (VC) and bioinoculants had a notable impact on Agronomic Efficiency (AE) and Partial Factor Productivity (PFP) in maize cultivation, as illustrated in Table 7.

Agronomic Efficiency (AE)

AE represents the grain yield increase per unit of nutrient applied, indicating how efficiently the plant utilizes the supplied nutrients. Among the tested treatments, the highest AE values were observed in the combination of micronutrient mixtures enriched with vermicompost and supplemented with ZSB bioinoculants. This suggests a synergistic interaction where bioinoculants improve nutrient availability and uptake, thereby optimizing nutrient utilization efficiency. In contrast, treatments involving only micronutrient mixtures or those enriched with farmyard manure (FYM) exhibited comparatively lower AE values. This implies that although these amendments contribute to yield improvement, their efficiency is significantly enhanced when used in conjunction with bioinoculants. The effective nutrient management practices, particularly balanced fertilizer applications, can substantially enhance AE in maize, these results are consistent with the findings of study (32).

Partial Factor Productivity (PFP)

PFP evaluates the grain yield obtained per unit of nutrient applied, offering insights into the overall efficiency of nutrient inputs. The study revealed that treatments incorporating micronutrient mixtures along with vermicompost and bioinoculants exhibited the highest PFP values. This suggests that these integrated nutrient management strategies enhance yield productivity per unit of nutrient supplied. Conversely, treatments involving only micronutrient mixtures recorded lower PFP values, highlighting the benefits of combining organic amendments and bioinoculants to improve nutrient use efficiency. These findings are consistent with the research conducted on groundnut, which demonstrated that integrating organic manures significantly improved PFP and seed yield (33). The integration of micronutrient mixtures with organic amendments such as vermicompost and bioinoculants, including ZSB, plays a crucial role in enhancing Agronomic Efficiency (AE) and Partial Factor Productivity (PFP) in maize cultivation depicted in Table 7. This improvement is primarily due to increased nutrient availability, as bioinoculants facilitate the solubilization and mobilization of nutrients, making them more accessible to plants. For instance, ZSB enhances zinc availability by converting its unavailable forms into plant-absorbable ones, thereby promoting better growth and higher yields. Additionally, organic amendments like vermicompost contribute to improved soil structure and encourage the proliferation of beneficial microbial populations, leading to better root development and enhanced nutrient uptake. Research suggests that these amendments not only increase soil fertility but also support sustainable crop production (34). Furthermore, the synergistic effect created by the combined use of organic and inorganic nutrient sources, along with bioinoculants, enhances nutrient use efficiency and crop productivity. This integrated approach aligns with sustainable agricultural practices aimed at reducing chemical fertilizer dependency and minimizing environmental impact (35). Therefore, adopting integrated nutrient management strategies that incorporate micronutrient mixtures with organic amendments and bioinoculants can significantly boost maize

Table 7. Eigenvalues of mean morphological and yield performance of maize under various organic manure and inorganic treatment regimes

Principal component	Eigenvalue	Percentage of variance	Cumulative percentage of variance
PC1	9.688	96.877	96.877
PC2	0.145	1.451	98.328
PC3	0.094	0.944	99.272
PC4	0.039	0.393	99.665
PC5	0.022	0.223	99.888
PC6	0.006	0.058	99.946
PC7	0.003	0.032	99.979
PC8	0.001	0.013	99.992
PC9	0.001	0.008	100
PC10	0	0	100

productivity. These practices not only improve crop yield but also contribute to soil health and long-term agricultural sustainability.

Effect of organic manures and inorganic fortified organics on the microbial population in sodic soil

The microbial population, including bacterial, fungal and actinomycete counts, exhibited significant variations across treatments incorporating vermicompost (VC), micronutrient (MN) mixtures and bioinoculants (ZSB). The highest bacterial count (21.42 × 10^6 CFU/g soil) was recorded in the treatment where the MN mix at 25 kg ha^{-1} was enriched with VC (1:10) and supplemented with ZSB, indicating that bioinoculants promote bacterial proliferation by enhancing nutrient availability and creating favorable rhizospheric conditions. Similarly, treatments combining VC and ZSB demonstrated greater bacterial populations compared to those with only MN or FYM enrichment, the role of bioinoculants in stimulating microbial colonization and nutrient mobilization was consistent with the findings was highlighted (36). The fungal population followed a comparable trend, with the highest count (13.24 × 10^5 CFU/g soil) observed in the MN mix at 25 kg ha^{-1} enriched with VC (1:10) + ZSB depicted in Table 8. The organic matter in vermicompost provides a suitable environment for fungal growth, facilitating decomposition and soil fertility improvement, reported that vermicompost enhances fungal biomass due to its aeration and moisture-retaining properties was noted (37). Actinomycetes, which contribute to organic matter decomposition and disease suppression, showed a peak count of 7.38 × 10^4 CFU/g soil in treatments combining VC-enriched MN mixtures with ZSB. This increase suggests a synergistic interaction between bioinoculants and organic amendments, leading to improved microbial diversity. The actinomycetes thrive in soils enriched with organic amendments, contributing to soil health and plant growth was demonstrated (38). Overall, the study highlights that integrating micronutrient mixtures with vermicompost and bioinoculants significantly enhances microbial populations, playing a crucial role in nutrient cycling and soil fertility. The highest microbial counts were recorded in treatments enriched with VC (1:10) + ZSB, reinforcing the value of organic amendments and beneficial microbes in promoting sustainable soil management.

Genetic diversity

Principal Component Analysis

The PCA helps to identify the relationships between traits and the independent principal components significantly influencing plant characteristics (39). The PCA method was used to simplify the dataset while retaining important information, particularly when handling multiple variables such as growth and yield characteristics. It helped identify key variables by determining which factors, including specific organic amendments, micronutrient levels and growth metrics, contributed most substantially to maize growth and yield variations. Additionally, PCA enabled pattern recognition, facilitating the identification of patterns and groups within the data to better understand how different treatments, such as organic manures and inorganic sources, affected maize performance in sodic soil. The multivariate data was also visually interpreted, demonstrating the connections between treatments and their impact on maize growth and production (40). These findings align with the studies (41).

Evaluation of maize physiological and yield performance under varying organic and inorganic treatments

PCA results revealed that PC1 had the highest eigenvalue (9.688) and explained 96.877 % of the variance, demonstrating that the majority of data variability was captured by this primary component (Table 9). The scree plot (Fig. 2) shows how much variation is explained by each principal component. The cumulative variance of the first two components (PC1 and PC2) reached 98.328%, indicating that these components were nearly sufficient to account for all the variance in the dataset. Subsequent components contributed only marginally, with the cumulative variance achieving 100 % by PC9, while PC10 contributed nothing. Regarding the contribution of variables to principal components, PC1 was predominantly influenced by cob girth (10.284), grain weight (10.244), stem girth (10.209), leaf area per plant (10.039) and plant height (10.091), highlighting their strong impact on this main component. PC2 was primarily driven by cob length (12.475), the number of kernels per row (18.817) and stem girth (4.203), underscoring the significance of yield components in this dimension. PC3 was mainly associated with the number of kernels per row (45.497), highlighting its critical significant role in determining maize yield. For PC4,

Table 8. Percent contribution of variables on principal components of mean morphological and yield performance of maize under various organic manure and inorganic treatment regimes

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Plant height	10.091	7.474	3.471	7.057	23.257	3.382	0.007	1.51
No. of leaves/Plant	10.19	5.432	1.935	1.966	6.727	8.225	0.009	2.669
Leaves area/Plant	10.039	11.694	2.182	2.587	29.36	8.625	6.011	3.533
Stem girth	10.209	2.403	5.06	4.037	0.268	7.221	8.127	29.883
Cob length	9.769	12.475	20.41	33.739	12.141	0.073	7.658	0.61
Cob girth	10.284	0.455	0.021	0.35	0.09	24.845	34.018	21.701
No. of rows/cob	10.081	2.956	13.991	0.04	13.751	43.532	6.93	0.469
No. of kernels/row	9.563	18.817	45.497	7.593	0.164	2.776	0.821	2.927
No. of kernels/cob	9.531	38.247	6.725	32.099	9.812	0.38	0.135	0.123
Grain weight	**10.244**	**0.047**	**0.709**	**10.532**	**4.429**	**0.941**	**36.419**	**36.575**

Table 9. Effect of organic manures and inorganic sources on Agronomic Efficiency and Partial Factor Productivity (kg grain/kg micronutrient) in hybrid maize

Treatments	Grain yield (Kg/ha)	Agronomic Efficiency (AE) (kg grain/kg micronutrient)	Partial Factor Productivity (PFP) (kg grain/kg micronutrient)
T_1	3064^{h}	-	-
T_2	3638^{g}	22.96^{i}	145.52^{i}
T_3	3975^{f}	36.44^{h}	159.00^{h}
T_4	4536^{c}	58.88^{e}	181.44^{e}
T_5	4478^{cd}	56.56^{e}	179.12^{ef}
T_6	4307^{de}	49.72^{f}	172.28^{fg}
T_7	4235^{e}	46.84^{g}	169.40^{g}
T_8	5594^{a}	101.20^{a}	223.76^{a}
T_9	5376^{a}	92.48^{b}	215.04^{b}
T_{10}	4971^{b}	76.28^{c}	198.84^{c}
T_{11}	4769^{b}	68.20d	190.76^{d}
SE(d)	109.69	1.35	3.31
CD(P=0.05)	228.81	2.81	6.91

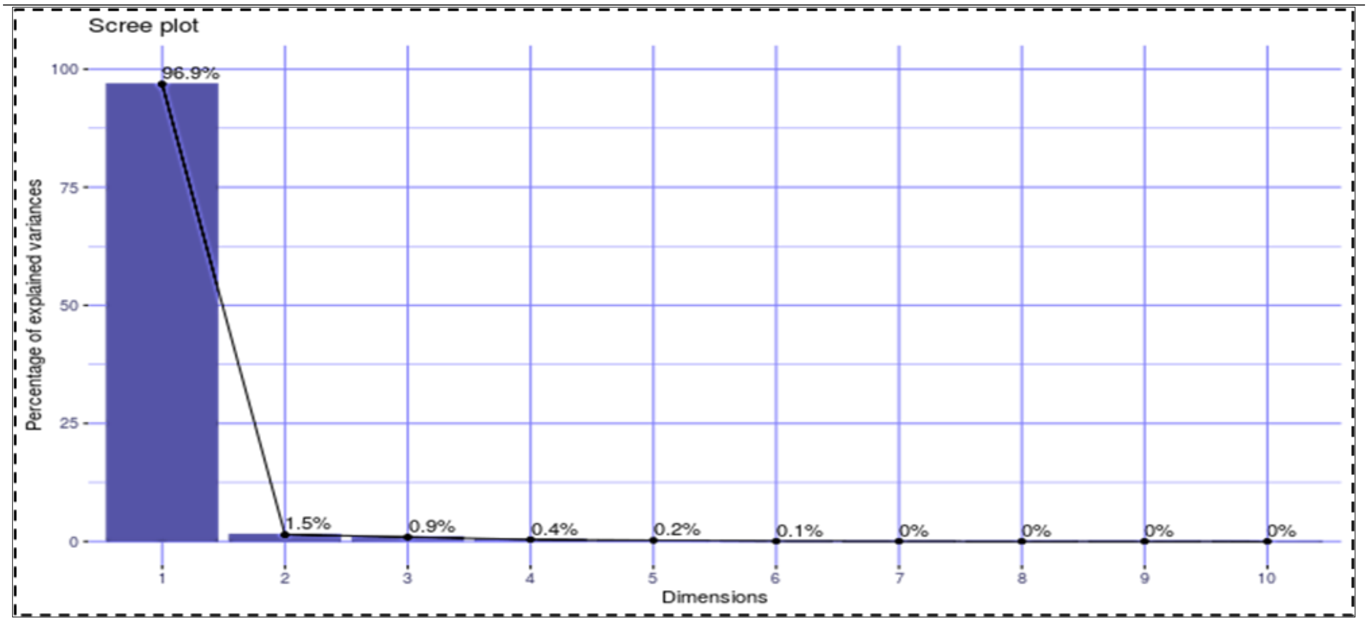

Fig. 2. Scree plot of variables of mean morphological and yield performance of maize under various organic manure and inorganic treatment regimes.

cob length (33.739) was the most influential variable, demonstrating its unique contribution in defining maize ear size and potential grain yield. PC5 to PC8 contributed less variance but still influenced specific traits such as stem girth, the number of rows per cob and cob girth, albeit with a smaller effect. Overall, PC1 effectively summarized the growth and yield performance of maize under various organic and inorganic treatments, with biomass and cob-related characteristics being the most impactful. PC2 and PC3 offered further insights into specific traits such as cob length and kernel numbers, aiding in distinguishing between treatments with more nuanced effects. The strong influence of PC1 indicated that most treatment effects could be captured within this component, simplifying the interpretation of treatment-induced variations in maize performance. The biplot provides a visual representation of how various treatments, including micronutrient mixtures, enriched vermicompost and ZSB applications, influence soil and plant properties. The direction and length of the arrows indicate the strength of each parameter's contribution to the principal components. Parameters that are closely grouped, such as the number of rows per cob, the number of kernels per row, grain weight and plant height exhibit strong positive correlations, whereas those pointing in opposite directions suggest a negative relationship. The distribution of treatments across the plot highlights their varying impacts on soil and plant characteristics, with those positioned closer to specific parameter vectors demonstrating a stronger association with those factors. Notably, parameters with longer arrows, such as SOC, GW and OC, contribute more significantly to variability within the dataset. The placement of treatments in different quadrants indicates their distinct effects, with enriched vermicompost and ZSB applications appearing to enhance soil health by improving organic carbon levels and microbial activity. In contrast, micronutrient mixtures alone may exhibit a different mode of influence, potentially affecting other soil or plant properties. This visualization aids in understanding how different formulations contribute to soil fertility and plant growth dynamics (Table 10, Fig. 3 and 4). These findings align with previous principal component analyses of growth and yield traits (41).

Table 10. Effect of organic manures and inorganic sources on the microbial population in sodic soil

Treatments	Bacterial (× 10^6/g soil)	Fungi (× 10^5/g soil)	Actinomycetes (× 10^4/g soil)
T_1	17.92	11.74	6.40
T_2	18.01	11.89	6.53
T_3	18.48	11.98	6.61
T_4	19.12	12.14	7.01
T_5	18.72	11.97	6.94
T_6	18.24	11.68	6.85
T_7	18.39	11.23	6.73
T_8	21.42	13.24	7.38
T_9	20.11	12.79	7.25
T_{10}	19.89	12.55	7.17
T_{11}	19.53	12.39	7.09
SE(d)	0.02	0.02	0.02
CD(P=0.05)	0.03	0.04	0.05

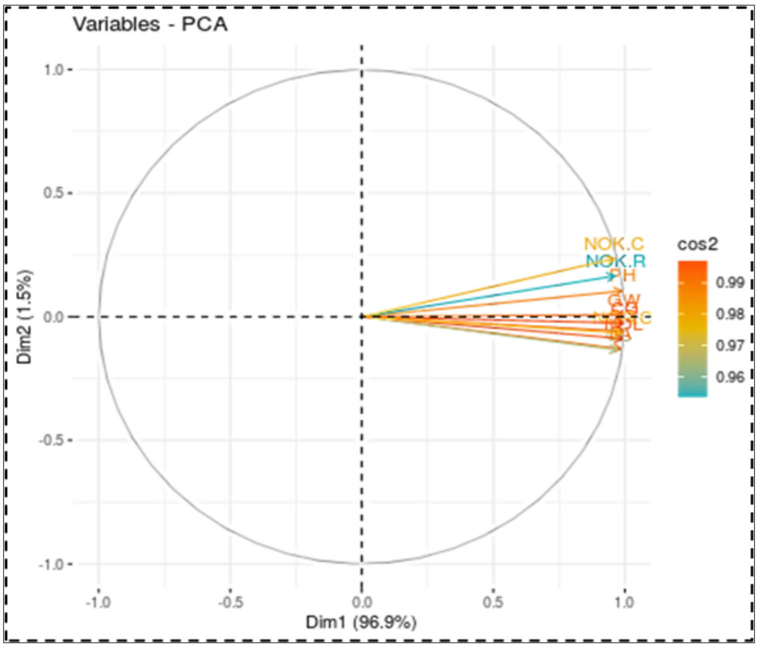

Fig. 3. Contribution of variables on a principal component of Maize Physiological and Yield Performance under Varying Organic and Inorganic Treatments. Note: PH (Plant height), NOL/P (No. of leaves/plant), LA (Leaf area), SG (Stem girth), CL (Cob length), CG (Cob girth), NOR/C (No. of rows/cob), NOK/R (No. of kernels/row), NOK/C (No. of kernels/cob), GW (Grain weight).

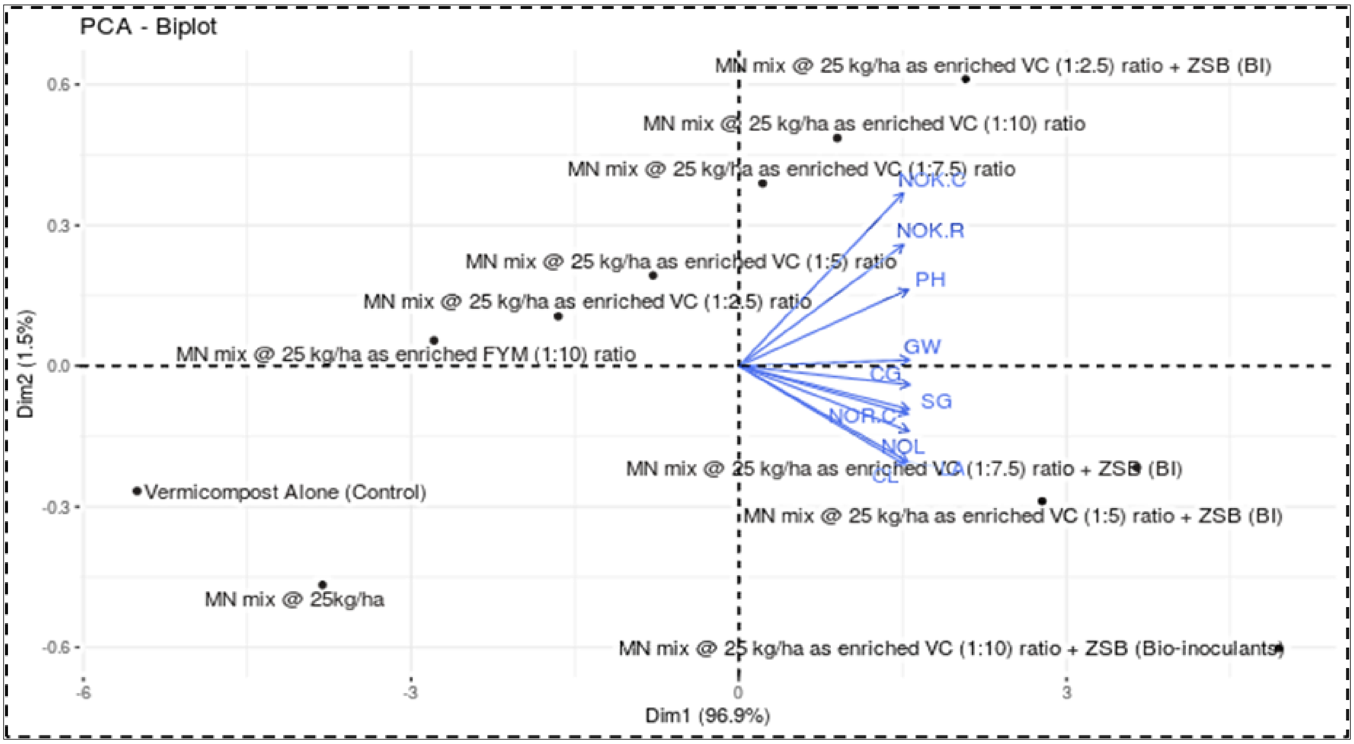

Fig. 4. Visualizing treatment impact: biplot analysis of maize performance.

Conclusion

This study demonstrates that the growth and yield traits of maize cultivated in sodic soil are significantly improved by the combined application of micronutrient-enriched vermicompost (VC) and bio-inoculants. Among the treatments, T8 (MN mixture at 25 kg ha^{-1} with enriched VC at a 1:10 ratio and Zn-solubilizing bacteria) showed the highest performance in plant height, leaf count, leaf area, stem girth, cob length, cob girth, kernel count and grain weight, with significant improvements over other treatments. The findings highlight the importance of microbial inoculation and micronutrient enrichment in enhancing photosynthetic efficiency, enzymatic activity, nutrient availability and overall crop yield. The results further suggest that integrating organic and inorganic nutrient sources, particularly enhanced VC with bio-inoculants, provides a sustainable strategy for improving maize performance under challenging soil conditions. Statistical analysis confirming significant differences among treatments suggests that targeted micronutrient applications are essential when combined with organic amendments to achieve optimal maize growth and yield. These findings reinforce the potential of enriched organic manures in sustainable agriculture, demonstrating their effectiveness in improving soil fertility, promoting plant growth and increasing maize productivity. Experimental results suggest an optimal application strategy consisting of 25 kg ha^{-1} of micronutrient mixture, vermicompost enriched at a 1:10 ratio and ZSB bioinoculants, incorporated into the soil before sowing, with an optional top-dressing during the vegetative stage. These recommendations can be adjusted based on soil test results and environmental factors. Effective policy implementation can enhance adoption through financial incentives, integration into soil health programs and certification systems to ensure the quality of enriched vermicompost. Furthermore, investments in research, farmer education and sustainability initiatives such as climate-smart agriculture and organic farming support can promote widespread utilization. By adopting these measures, policymakers can drive sustainable soil management, leading to improved crop yields and long-term agricultural resilience.

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Authors' contributions

DM carried out the experiment, work plan and methodology, took observations, analyzed the data and wrote the draft manuscript; MB carried out the Work plan, Conceptualization, providing funding acquisition, methodology, supervision and coordinated the work TU and AGM contributed by imposing the experiment, laboratory analysis, reviewing and Editing; TS helped in summarizing and revising the manuscript; SR and KS coordinating the work, methodology and editing; NM helped in editing, summarizing and revising the manuscript; MV carried out work plan, conceptualization.

Compliance with ethical standards

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

Ethical issues: None

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