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Impact of Organic Fertilizer Substitution on Soil Quality and Microbial Diversity in Maize Ecosystems

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Abstract

This study addresses the global issue of soil degradation and the decline in soil quality caused by excessive fertilizer use. Field experiments were conducted in the Northeast Black Soil Region and the North China Plain to evaluate the potential of organic fertilizer as a substitute for chemical fertilizers. Four treatment groups were established: control with no fertilization (CK), pure chemical fertilizer (T0), 25% organic fertilizer substitution (T25), and 50% organic fertilizer substitution (T50). The study systematically analyzed changes in soil physical and chemical properties, organic carbon fractions, microbial communities, and maize yield. The results showed that organic fertilizer substitution significantly reduced soil bulk density and pH, while increasing available phosphorus, potassium content, and various active organic carbon components (DOC, MBC, POC, ROC) by 28.21%–52.97%. The T25 treatment resulted in a 194.1% and 30.17% increase in carbon pool management index and activity index, respectively, while also promoting microbial diversity and the abundance of functional microbial groups. Nitrogen fertilizer utilization efficiency increased by 17.95%–33.33%, and maize yield traits were significantly optimized. In conclusion, 25% organic fertilizer substitution is the optimal ratio for improving soil quality, microbial activity, and maize yield.

Keywords: organic fertilizer substitution; soil quality; carbon storage; varieties of microorganisms; maize production

Introduction

As the use of chemical fertilizers continues to increase in global agricultural production, changes in soil quality and microbial communities have become critical issues that need urgent attention. The excessive reliance on fertilizers, especially nitrogen fertilizers, has led to a significant reduction in soil organic matter and the deterioration of soil structure [1]. This vicious cycle accelerates soil acidification and disrupts the structure of soil microbial communities. This not only reduces the diversity of beneficial soil microorganisms but also creates a favorable environment for the proliferation of pathogens, ultimately affecting crop growth and health [2,3]. Therefore, finding sustainable agricultural technologies to replace chemical fertilizers and improve soil quality has become crucial.

When it comes to enhancing soil quality, organic fertilizers have emerged as a cornerstone of sustainable farming practices worldwide [4,5]. Organic fertilizer can not only increase soil nutrient content, regulate soil pH and other chemical properties [6,7], but also significantly improve its physical properties. Studies have shown that organic fertilizers promote the aggregation of soil particles, enhancing the stability of soil structure, which in turn increases soil porosity and permeability [8]. Moreover, organic fertilizers optimize soil water management, increase the number of macropores, and improve water infiltration and drainage capacity, effectively reducing water accumulation [9,10]. The combined application of organic and inorganic fertilizers can further enhance efficiency, with inorganic fertilizers providing nutrients that maize can rapidly absorb, while organic fertilizers release nutrients gradually, meeting maize's needs at different growth stages. This long-term nutrient release balance enhances maize growth rate and stress resistance, while also improving the availability of key soil elements like nitrogen and phosphorus, thereby avoiding nutrient waste and environmental pollution [11]. The appropriate ratio of organic fertilizer substitution is crucial for maize growth. Numerous studies have shown [12] that replacing 20-30% of inorganic fertilizers with organic fertilizers effectively promotes dry matter accumulation, nutrient absorption, and nitrogen utilization in crops.

Soil organic carbon fundamentally underpins soil vitality and nutrient accessibility while stimulating microbial metabolic processes, improves the diversity and stability of microbial communities, and thereby enhances overall soil quality and ecological function. In agricultural production, organic fertilizers promote soil health by providing the

necessary nutrients for plants, supporting the continued growth of maize. Scientific findings suggest that incorporating organic fertilizers boosts the introduction of external carbon, which substantially elevates soil organic carbon concentrations, thereby fortifying both carbon storage and biological activity within the soil [13].

The microscopic life within soil plays an indispensable role in nutrient recycling, decomposing organic materials, and keeping pathogens in check. Applying organic fertilizers gives the soil's microbial makeup a leg up, paving the way for richer arrays of bacteria and fungi. This not only enhances the nutrient conversion capacity of the soil but also improves its water retention ability. As microbial community diversity and activity increase, the self-healing capacity of soil and nutrient cycling efficiency are also enhanced. Enhanced soil microorganism levels accelerate organic breakdown and nutrient transformation, thereby boosting maize's water and nutrient uptake efficiency, while enhancing its resistance to stress. These changes help reduce disease occurrence, and by regulating the composition of soil microbial communities, organic fertilizers also improve soil resilience and adaptability.

The integrity of the soil is crucial for maintaining the ecological balance and keeping agricultural output sustainable. It's the backbone of ensuring that our soil keeps chugging along, doling out nutrients and hanging onto water to nurture our crops [6,14]. When it comes to gauging soil quality, the old standbys like organic content, pH levels, and bulk density are the go-to metrics. But as we zoom in on soil vitality, we're incorporating more biological markers into the mix [15]. A holistic approach, tying organic carbon to soil health, birthed the Soil Quality Index (SQI) as a mighty tool for checking up on soil well-being. It delves into the soil's physical, chemical, and biological quirks to paint a clear picture of how organic additions are boosting soil quality [16,17]. Given that soil attributes often play nice in a group, cranking out the SQI often hits a snag with data overload and computational hurdles. That's why we've got dimension-diminishing tricks up our sleeve, like PCA, MDS, and RDA, which zap the redundancy and zero in on what's key in the soil quality game [18].

Our research is set to dissect how different farming fertilizers impact the soil's health, the microbial scene, and the crop harvest. It's all about figuring out if organic fertilizers can step in for the chemical kind and lay down the groundwork for a more eco-friendly approach. By exploring the soil's relationship with its tiny residents, we'll fill in the blanks in current research and champion the organic fertilizers as a green, go-to option in the fight against chemical dependence.

Methods

Study area and characteristics of soil properties

The study took place at the Modern Science and Technology Park within Tongliao's Agricultural and Animal Husbandry Research Institute, located in Inner Mongolia (Figure 1). The area features a typical temperate monsoonal climate characteristic of continental interiors, characterized by plenty of sunshine and sharply defined seasonal changes. Annual rainfall typically falls between 350 and 400 mm, while evaporation rates hit roughly 1200.0 mm per year. During the maize cultivation period from May to October, average temperatures reach approximately 19.13°C, with precipitation averaging a modest 6.6 mm (Figure 2). The fertile black soil in the area is ideal for cultivating maize, soybeans, wheat, and similar crops. Initial soil analysis revealed a slightly alkaline pH of 8.16, with a moisture content of 13.28%. Key nutrient levels included total nitrogen (0.53 $g \cdot kg^{-1}$), available phosphorus (0.81 $g \cdot kg^{-1}$), total potassium (0.14 $g \cdot kg^{-1}$), and organic carbon (15.92 $g \cdot kg^{-1}$).

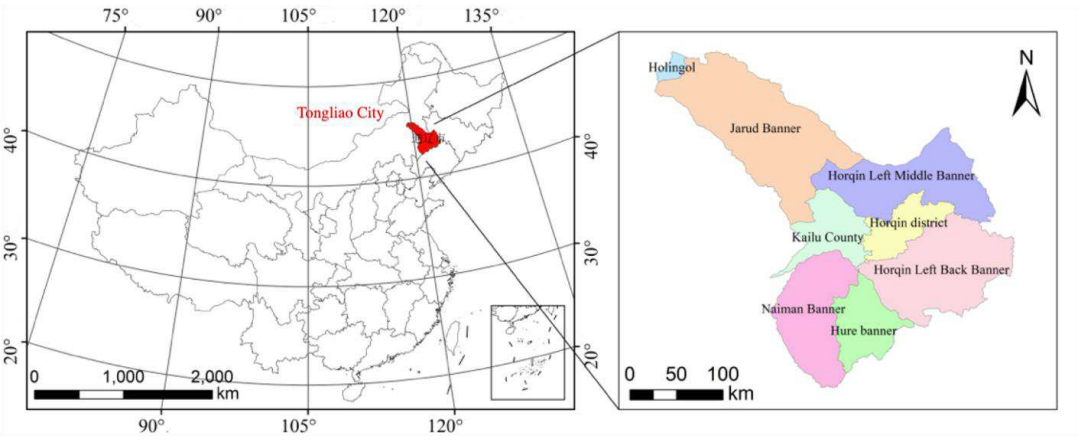


Figure 1. Experimental site location map

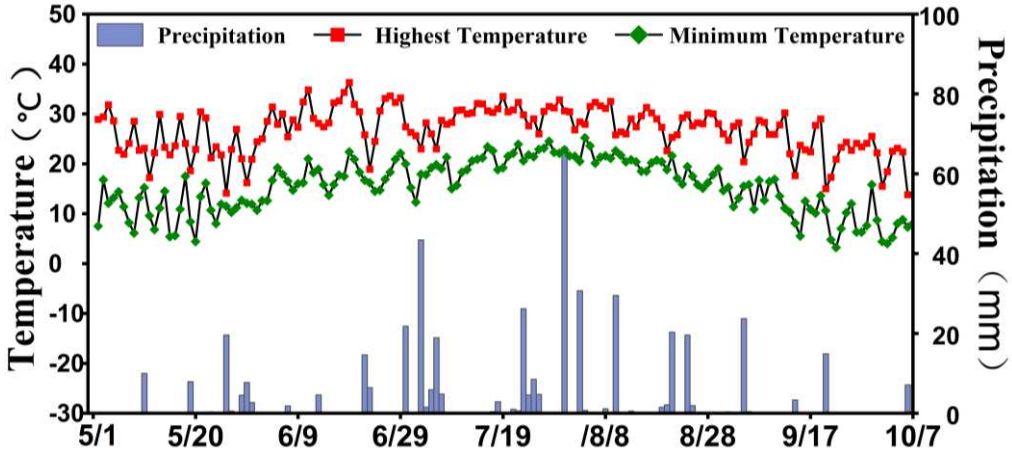


Figure 2. Maximum and minimum temperatures and precipitation during the maize growing season

Experimental design. This experiment included four fertilization treatments: CK (no fertilization), T0 (chemical fertilizer only), T25 (organic fertilizer replacing 25% of chemical nitrogen fertilizer), and T50 (organic fertilizer replacing 50% of chemical nitrogen fertilizer). Prior to planting, a compound N–P–K fertilizer was applied as the base fertilizer for all treatments. For T25 and T50, organic fertilizer was mixed into the soil before sowing, and nitrogen fertilizer was applied only at key growth stages (seedling, jointing, tasseling, and filling stages). The chemical fertilizers used were urea (N 46%), calcium superphosphate (P_2O_5 18%), and potassium sulfate (K_2O 52%). The organic fertilizer used was "Mengnong Fertilizer," with total nutrients ($N+P_2O_5+K_2O$) > 4% and organic matter > 30%. To ensure consistent phosphorus (P) and potassium (K) inputs, T25 and T50 replaced 25% and 50% of the chemical nitrogen fertilizer with an equivalent amount of nitrogen from organic fertilizer, while adjusting the chemical fertilizer ratios to maintain consistent total inputs of nitrogen (N), phosphorus (P), and potassium (K) across treatments.

Based on the medium-level irrigation reference from the local standards of Inner Mongolia Autonomous Region, "Technical Regulations for Water and Fertilizer Management under Drip Irrigation in Maize," and considering local conditions, the irrigation amount was set at 160 m^3 per mu. Drip irrigation was used, with one drip tape placed between two rows of maize, arranged with a row spacing of 40 cm. The spacing between the drip tapes was 110 cm. Irrigation was applied at the same time as the fertilization treatments during the maize seedling, jointing, tasseling, and filling stages. Experimental plots, with three replications per treatment, covered 80 m^2 (10 m × 8 m) each. They included a 1 m wide pathway in the center and a 2 m wide protected tillage strip around the perimeter. The maize variety TK601, commonly grown in the area, was selected for the experiment. The sowing date was May 10, 2024, with a planting density of 4500–5000 plants per mu.

Table 1. FertilizerFertilizer treatments and application rates

	Organic Fertilizer Input（kg·hm^{-2}）			Fertilizer Input（kg·hm^{-2}）			Supplemental Fertilizer Amount（kg·hm^{-2}）		
Target	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
CK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T0	0.00	0.00	0.00	45.00	67.50	56.25	0.00	11.25	11.25
T25	11.25	5.63	5.63	33.75	67.50	56.25	0.00	5.63	5.63
T50	22.50	11.25	11.25	22.50	67.50	56.25	0.00	0.00	0.00

Data collection

Sample collection. At the peak of maize grain development, we gathered five soil specimens from each plot at random, combined them thoroughly, and filtered out any unwanted materials like pebbles, root systems, and other foreign particles. Using the quartering technique, we split the composite samples into approximately 500 gram sections, which were subsequently air-dried and sifted through 2 mm and 0.25 mm meshes to prepare for analysis of various soil characteristics. Six maize plants displaying consistent development patterns were chosen as representative samples. For each plant, we extracted root systems from the topsoil layer (0-20 cm), removing clinging dirt by means of a vigorous shaking technique. These soil samples were then placed in sterile containers and preserved under dry ice during transport to our laboratory, where they were maintained at 4°C until further examination.. A 200 g sample was subjected to 16S rDNA amplicon sequencing to assess microbial diversity using the following steps: PCR amplification, Miseq library construction, Miseq sequencing, and 16S rDNA data processing. For yield measurement, a diagonal sampling method was used, with sampling points taken at the front, middle, and back along the diagonal of the plot. A 5-meter-long single row of maize was selected for each sampling point. All ears were harvested, weighed to determine total ear weight, and the total number of ears was counted to calculate the average fresh weight per ear. Ten representative ears were selected to measure kernel weight, moisture content, and maize yield.

Determination of soil physicochemical properties. In this study, soil physical properties were determined using the ring-core method [19], including bulk density (BD), total porosity (SP), and soil moisture content (SMC). The initial mass of the ring with field-moist soil was recorded as m_1, the mass after water absorption as m_2, the mass after oven drying as m_3, and the empty ring mass as m_0. The calculation formulae for each indicator are given below. The calculation of bulk density is as follows:

$$\rho_b = \frac{m_3 - m_0}{V} \quad (1)$$

In this equation, ϱb denotes the soil bulk density (g·cm^{-3}), and V is the volume of the ring core (cm^3). The soil water content was calculated using Equation (2).

$$\theta_g = \frac{m_1 - m_3}{m_3 - m_0} \quad (2)$$

θ_g denotes the soil water content (%).

$$P_t = \left(1 - \frac{\rho_b}{\rho_d}\right) \quad (3)$$

Pt denotes total soil porosity (%); ϱd is soil (particle) density, typically 2.65 g·cm^{-3}; ϱb is the bulk density as defined in Eq. (1).

The determination of soil chemical properties was carried out following the method outlined by Lu [20]. Soil pH was measured with a Mettler Toledo pH meter (Switzerland) using a 1:2.5 soil-to-water ratio. The soil samples were air-dried, ground, and sieved through a 2 mm mesh. An extraction solution was made with a 5:1 soil-to-water ratio, shaken for 5 minutes, and left to stand for 30 minutes. Total nitrogen (TN) underwent Kjeldahl analysis (KDN-812, Shanghai, China) following sulfuric acid digestion. [21]. To isolate available phosphorus (AP), we utilized a 0.5M sodium bicarbonate bath with a balanced pH of 8.5, followed by quantification through the molybdenum blue assay. For assessing available potassium (AK), we extracted the sample with a 1M ammonium acetate solution, employing a soil-to-water ratio of 1:10, and measured the results via a flame photometer model FP640, courtesy of Shanghai Precision Instrument Co., Ltd., in Shanghai, China [20]. The soil organic carbon (SOC) content was calculated using the potassium dichromate oxidation process [22]. To acquire dissolved organic carbon (DOC), we blended 10 grams of soil with 50 mL of solution, shook it for half an hour, and then filtered it through a 0.45-micron sieve. The filtered material was then evaluated using a TOC analyzer from Agilent, located in Jena, Germany [23]. The level of easily oxidizable organic carbon (ROC) was established through the KMnO4 oxidation and colorimetric analysis at a concentration of 333 mol·L^{-1} [23]. The total organic carbon content, also referred to as POC, was analyzed using the potassium dichromate oxidation method, as detailed in reference [24]. Additionally, microbial biomass carbon, known as MBC, was measured using the chloroform fumigation-extraction technique, as outlined in source [25].

Measurement of carbon storage management index. The carbon storage Activity (CA) serves as a barometer for how quickly carbon undergoes transformation and mineralization in soil, effectively capturing the dynamic nature of soil carbon metabolism. By examining the relationship between readily oxidizable carbon and total organic carbon, this metric sheds light on the rate at which carbon breaks down in soil systems. The carbon storage Management Index (CPMI) combines the carbon storage index and activity index to paint a complete picture of how various soil man-

agement approaches influence carbon storage and biological activity in the ground. Researchers gathered soil specimens by taking random samples from various representative locations throughout the study zone, then combined, air-dried, and sifted them. To determine the soil organic carbon content, they utilized the potassium dichromate oxidation method. Easily oxidized carbon (ROC) was also measured using the same method. In this method, the easily oxidized carbon in the soil is oxidized at a certain temperature, and the change in absorbance of the reaction solution is measured using a spectrophotometer to calculate the ROC content. This experiment used CK as the reference soil and followed the method of Jiang et al. for calculation [26] :

$$CA = \frac{ROC}{(SOC-ROC)} \tag{4}$$

$$CAI = \frac{A}{CA} \tag{5}$$

$$CPI = \frac{SOC_{sample}}{SOC_{CK}} \tag{6}$$

$$CPMI = CPI \times CAI \times 100 \tag{7}$$

Determination of soil microbial communities. In order to delve deeper into the makeup and range of soil microorganisms, the research utilized 16S rRNA gene sequencing and ITS region analysis, which were both amplified and then subjected to high-throughput sequencing techniques. The DNA from each soil sample was meticulously extracted using the Nucleospin DNA Extraction Kit, a product sourced from Georgia, USA, and DNA concentration and quality were assessed using agarose gel electrophoresis and a UV spectrophotometer. Bacterial communities were characterized by amplifying the V3-V4 hypervariable region of 16S rRNA with primers 338F/806R, while fungal analysis targeted the ITS1 region using primer pair ITS1F/ITS2R. After PCR products were purified and their concentrations measured, The Illumina sequencing platform was employed for high-throughput sequencing, and the resulting data underwent processing through the analytical toolkit on the Novogene Cloud Platform. This step yielded amplicon sequence variant (ASV) sequences along with their corresponding abundance details.

Measurement of maize growth indicators and yield. In the measurement of maize growth indicators, plant height was measured by randomly selecting 10 representative plants from each experimental group. The height was precisely measured using a ruler from the soil surface to the top of the maize plant. Leaf area was measured by selecting representative leaves at three growth stages from each treatment group, using a leaf area meter (LI-3100C) to ensure high-precision leaf area calculation. Aboveground biomass was measured by randomly selecting 10 representative plants from each experimental group. The fresh weight of the aboveground parts (including stems, leaves, ears, etc.) was recorded, and the samples were dried in an oven at 60-70°C until a constant weight was achieved. The dry matter weight was then precisely measured. The average aboveground biomass of each experimental group was calculated and converted to per unit area (per square meter or per hectare) aboveground biomass.

For yield measurement, a diagonal sampling method was used, with sampling points taken at the front, middle, and back along the diagonal of the plot. A 5-meter-long single row of maize was selected for each sampling point. All ears were harvested, weighed to determine total ear weight, and the total number of ears was counted to calculate the average fresh weight per ear. Ten representative ears were selected, the weight of the sample ear is equal to 10 times the average fresh weight of the ear, with an error of less than 0.05 kg. After threshing the sample ears, the kernel weight was measured, and the moisture content of the kernels was determined using a moisture meter (PM-8188). Finally, the dry grain yield was calculated by adjusting the moisture content to the standard of 14.0%.

Three plants with uniform growth were selected from each plot, and the organs were dried to a constant weight. The total nitrogen content in each plant organ was determined using the Kjeldahl method. The relevant nitrogen utilization indices were calculated according to the formula outlined in [27].

$$PNA(kg \cdot hm^{-2}) = U_N \times DM \tag{8}$$

$$NFP(kg \cdot kg^{-1}) = \frac{U_N - U_0}{N_{appl}} \times 100\% \tag{9}$$

$$NFUE(kg \cdot kg^{-1}) = \frac{Y_N - Y_0}{N_{appl}} \tag{10}$$

$$NFP(kg \cdot kg^{-1}) = \frac{Y_N}{N_{appl}} \quad (11)$$

Soil Quality Index Measurement (SQI). This research utilized the Soil Quality Index (SQI) to evaluate how irrigation and fertilization practices impact soil health, applying the total set methodology outlined in reference [28]. Drawing from 16 key soil indicators collected in 2024, we developed a tailored approach to compute the SQI. The scoring system operates as follows: each soil variable was first transformed into a standardized value (Si) between 0 and 1. For most parameters, we applied Equation (12) following the "more is better" principle, while Equation (13) was reserved for "less is better" cases. The sole exception was pH, which was uniquely assessed using Equation (10) due to its distinct optimal range characteristics.

$$Si' = \frac{(X_i - X_{min})}{(X_{max} - X_{min})} \quad (12)$$

$$Si'' = \frac{(X_{max} - X_i)}{(X_{max} - X_{min})} \quad (13)$$

In this context, Si′ and Si″ represent the scores for the i-th parameter, and X_i, Xmax, and Xmin denote the measured, maximum, and minimum values, respectively. Subsequently, the i-th parameter's weight (W_i) from principal component analysis (PCA) equaled its communality divided by the sum of all parameters' communalities.

Finally, the Soil Quality Index (SQI) was calculated using the following formula:

$$SQI = \sum_{i=1}^{n} Wi \times Si \quad (14)$$

Where n is the number of soil parameters, and Wi and Si are the weight and score of the i parameter, respectively[29].

Data processing

The research team employed one-way analysis of variance (ANOVA) to crunch the numbers on soil's physical, chemical, and biological characteristics. IBM SPSS Statistics 20.0 (hailing from Chicago, Illinois, USA) was the go-to tool for data wrangling and comparing averages, while Tukey's method stepped in to run multiple comparison tests at a significance threshold of $p<0.05$. To bring the analysis to life visually, OriginPro 9.1 software (courtesy of OriginLab Corporation in Northampton, MA, USA) was used to create the graphs. To get to the bottom of how variables were interconnected, the researchers turned to principal component analysis (PCA) and complex network analysis using R software (version 4.2.2)., while redundancy analysis (RDA) was performed using Canoco 5 to explore the impact pattern of environmental factors on soil ecological characteristics. Finally, the visualization of the network topology structure was completed by Gephi (version 0.9.2), comprehensively presenting the correlation patterns in multidimensional data.

Results

Impact of Organic Fertilizer Substitution on Soil Properties and Maize Yield

Soil physicochemical properties. Compared to the CK treatment, the T0, T25, and T50 treatments reduced soil bulk density (BD) and pH, with a slight decrease of 0.1, 0.17, and 0.2 units, respectively. Meanwhile, available phosphorus (AP) and total nitrogen (TN) showed an overall increasing trend, with increases ranging from 23.22% to 30.46% and 15.07% to 39.22%, respectively. When stacked against the T0 treatment, the T25 and T50 treatments really upped the ante, giving significant boosts to soil organic carbon (SOC), dissolved organic carbon (DOC), microbial biomass carbon (MBC), particulate organic carbon (POC), soluble organic carbon (ROC), and available potassium (AK). These improvements ranged from 12.21% to 19.91% for SOC, 28.21% to 31.53% for DOC, 21.09% to 35.46% for MBC, 34.08% to 44.85% for POC, 29.52% to 52.97% for ROC, and 13.36% to 27.96% for AK, showing quite the positive impact across the board.

Table 2. Organic Fertilizer Substitution Modifies Key Soil Characteristics

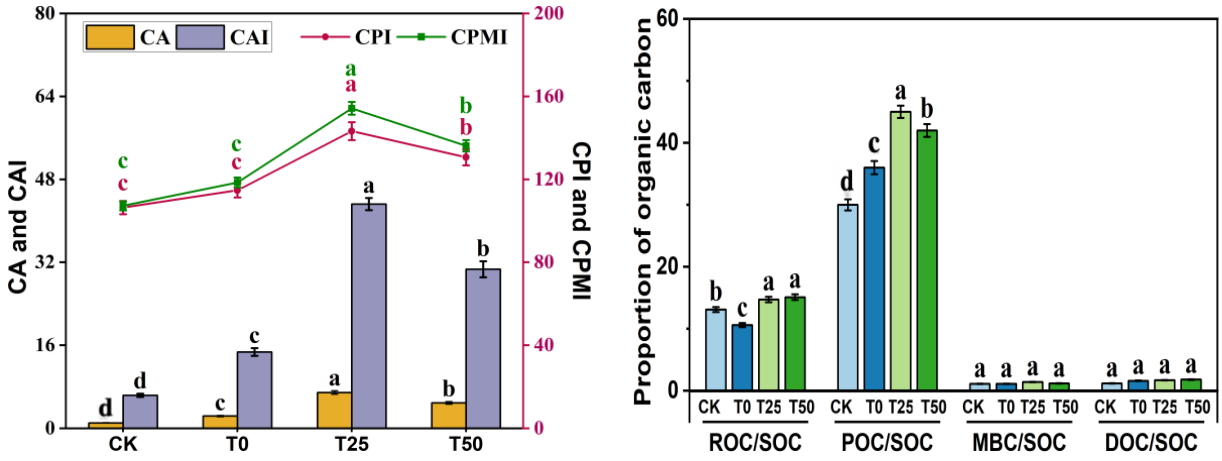
Processing group	**CK**	**T0**	**T25**	**T50**
BD($g \cdot cm^{-3}$)	1.65±0.05a	1.63±0.04a	1.58±0.10a	1.61±0.03a

SP(%)	46.71±0.80a	47.42±0.48a	48.91±0.68a	48.17±0.88a
SMC(%)	14.62±0.34a	14.91±0.32a	15.53±0.26a	15.12±0.56a
SOC($g \cdot kg^{-1}$)	16.89±0.14d	18.26±0.33c	22.83±0.41a	20.81±0.38b
DOC($mg \cdot kg^{-1}$)	245.65±0.78d	271.53±1.33c	396.58±0.42a	378.25±0.77b
MBC($mg \cdot kg^{-1}$)	187.32±5.56d	202.16±10.91c	313.27±2.52a	256.13±7.16b
POC($g \cdot kg^{-1}$)	5.71±0.23c	5.03±0.12c	9.12±0.36a	7.63±0.31b
ROC($g \cdot kg^{-1}$)	2.69±0.21c	2.22±0.25c	4.72±0.32a	3.15±0.19b
TN($g \cdot kg^{-1}$)	0.59±0.02d	0.73±0.04c	1.02±0.06a	0.91±0.03b
AK($g \cdot kg^{-1}$)	0.11±0.02b	0.12±0.01b	0.12±0.02b	0.13±0.01a
AP($mg \cdot kg^{-1}$)	86.34±0.81c	98.43±2.35a	87.21±1.84c	93.12±2.96b
pH	8.16±0.04a	8.08±0.03b	7.97±0.02c	8.01±0.03c
SQI	0.33±0.01d	0.52±0.01c	0.69±0.02a	0.62±0.01b

Data are presented as mean ± standard error (n=3), with lowercase letters indicating significant differences among treatments. Pearson correlation analysis detected differences at the 5% significance level ($p<0.05$). BD : Soil bulk density; SP : Soil porosity; SMC - Soil moisture content; SOC : Soil organic carbon; DOC : Dissolved organic carbon; MBC : Microbial biomass carbon; POC : Particulate organic carbon; ROC : Readily oxidizable organic carbon; TN : Total nitrogen; AP : Available phosphorus; AK : Available potassium.

Distribution of soil organic carbon and carbon storage index. The carbon storage Management Index, or CPMI, is a handy gauge for evaluating how various soil management methods affect the health of carbon reservoirs in the ground. It turns out that a higher CPMI score is a sure sign that soil quality is on the upswing (Figure 3-a). When it comes to the effectiveness of different fertilizer applications, our data revealed a clear pecking order: T25 came out on top, followed by T50, then T0, and finally the control (CK) treatment. Specifically, in terms of the carbon storage Index (CPI), T25 boasted an impressive 86% increase over CK, a 64.61% increase over T0, and a 20.17% leap over T50, making it the standout performer among all the treatments (this finding was statistically significant at $P < 0.05$). As for carbon storage activity (CA), the readings varied across treatments from 1.01 to 6.88, but there was no significant discrepancy in CA between CK and T0. The CAI value for T25 was 581.7%, 194.1%, and 41.1% higher than CK, T0, and T50, respectively. There were significant differences in CPMI among treatments ($P < 0.05$), with T25 being 43.87%, 30.17%, and 13.26% higher than CK, T0, and T50, respectively.

The proportion of each active organic carbon fraction within the total soil organic carbon (SOC) pool, which illustrates how these components are distributed (Figure 3-b). When comparing the various treatments, we found that the percentages of particulate organic carbon (POC), readily oxidizable carbon (ROC), and dissolved organic carbon (DOC) relative to total SOC differed significantly across all groups ($P < 0.05$). Except for DOC, the combined application of organic and inorganic fertilizers significantly increased the proportion of each active carbon component in SOC. Among all treatments, the proportion of POC in SOC was significantly higher than that of other active carbon components ($P < 0.05$), with a range of 29.78% to 47.85%. The ROC/SOC ratio for T50 was 15.27%, 42.25%, and 2.72% higher than CK, T0, and T25, respectively. The MBC/SOC ratio was the lowest, with a range of 1.11% to 1.37%. The proportion of DOC in the soil ranged from 1.2% to 1.88% across treatments.



(**a**) (**b**)

Figure3 carbon storage Management Index. (**a**) Key indicators for carbon storage assessment: CA (Carbon Activity): Measures the dynamic carbon processes within the pool; CAI (Carbon Activity Index): Quantifies the relative activity level of the carbon storage; CPI (carbon storage Index): Reflects the overall status of the carbon storage; CPMI (carbon storage Management Index): Evaluates the effectiveness of carbon storage stewardship. (**b**) The ratio of each constituent's carbon content to the total organic carbon.

Maize yield and fertilizer use efficiency. The T25 treatment resulted in the highest values for stem diameter, ear length, 100-grain weight, yield, and biomass, with values of 22.79 cm, 190.3 cm, 47.37 g, and 724.82 kg·acre^{-1}, respectively. The yield and biomass in T25 were increased by 28.48% and 32.19% compared to the control group. There were no significant differences in stem diameter, ear length, and 100-grain weight between T25 and T50. The T0 treatment had the highest plant height, and the T50 treatment had the highest leaf area. Organic fertilizer substitution significantly influenced maize nitrogen fertilizer productivity (NFP), nitrogen fertilizer agronomic efficiency (NFUE), and nitrogen use efficiency (NAE). Under the T25 treatment, NFP, NFUE, and NAE increased by 33.33%, 74.03%, and 66.67%, respectively, compared to T0, and by 13.04%, 27.96%, and 41.03%, respectively, compared to T50. For the T50 treatment, NFP, NFUE, and NAE increased by 17.95%, 36.01%, and 18.18%, respectively, compared to T0. These results indicate that reducing chemical fertilizer and co-applying organic fertilizers is a feasible approach, significantly improving maize yield and biomass. Notably, the fertilization method with 25% organic fertilizer substitution showed a uniform improvement in maize yield and growth characteristics, with a significant yield increase.

Table 3. Effects of organic fertilizer substitution on corn growth and yield

Processing group	CK	T0	T25	T50
Plant height （cm）	335.67±4.24b	345.01±4.41a	331.67±3.32b	335.12±3.28b
Stem diameter （cm）	17.79±0.37b	22.28±0.22a	22.79±0.31a	22.68±0.34a
Leaf area （%）	2.65±0.02c	2.73±0.03b	2.73±0.04b	2.89±0.08a
Panicle length （cm）	187.12±6.93b	190.13±1.73a	190.31±2.89a	189.74±5.86a
Hundred grain weigh (g)	42.99±0.95b	46.64±1.06a	47.37±1.23a	45.46±1.27a
Yield （kg·acre^{-1}）	564.14±10.71d	687.91±7.22c	724.82±3.56a	700.26±4.82b
NFP （%）	-	78.08±1.35c	104.02±2.56a	92.11±2.14b
NFUE （%）	-	20.83±0.69c	36.25±0.48a	28.33±0.55b
NAE （%）	-	33.01±0.91c	55.03±1.62a	39.08±2.13b

NFUE stands for Nitrogen Fertilizer Use Efficiency; NFP stands for Nitrogen Fertilizer Productivity; NAE stands for Nitrogen Agronomic Efficiency

The effect of reducing the application of organic fertilizer combined with chemical fertilizer on the microbial community of maize

Bacterial community structure. The total bacterial OTUs were 19,996 (Figure 4-a), with variations among treatments: CK (5263), T0 (5027), T25 (4842), and T50 (4864). Compared to the CK treatment, the T0, T25, and T50 treatments reduced bacterial abundance by 4.48%, 7.99%, and 7.58%, respectively. Notably, the T25 and T50 treatments also significantly decreased the bacterial Shannon index and Chao1 index by 0.221 and 0.251 units, and 453.41 and 549.01 units, respectively.

At the genus level, the top 20 genera comprised 40.06±2.25% of total sequences, (Figure 4-b) with Vicinamibacteraceae showing the highest average relative abundance at 5.43%, followed by Vicinamibacterales (4.63%), Gemmatimonadaceae (4.46%), and Nitrososphaeraceae (3.95%). Specifically, the T25 treatment significantly increased the abundance of Gemmatimonadaceae, Sphingomonas, and MND1 by 23.12%-28.99%, 55.54%-74.98%, and 13.99%-27.09% (Figure 4-c), respectively, compared to other treatments. In contrast to the T0 treatment, the abundance of Arthrobacter decreased in all treatments, with a reduction of 32.87%-78.45% .

Principal Coordinate Analysis (PCA) showed (Figure 4-d) that the first two axes explained 44.1% of the bacterial variation, with the first and second axes explaining approximately 27.91% and 16.19% of the bacterial variation, respectively. The T25 treatment group showed clear separation from the CK and T0 treatment groups along the first axis, indicating significant differences in microbial community structure.

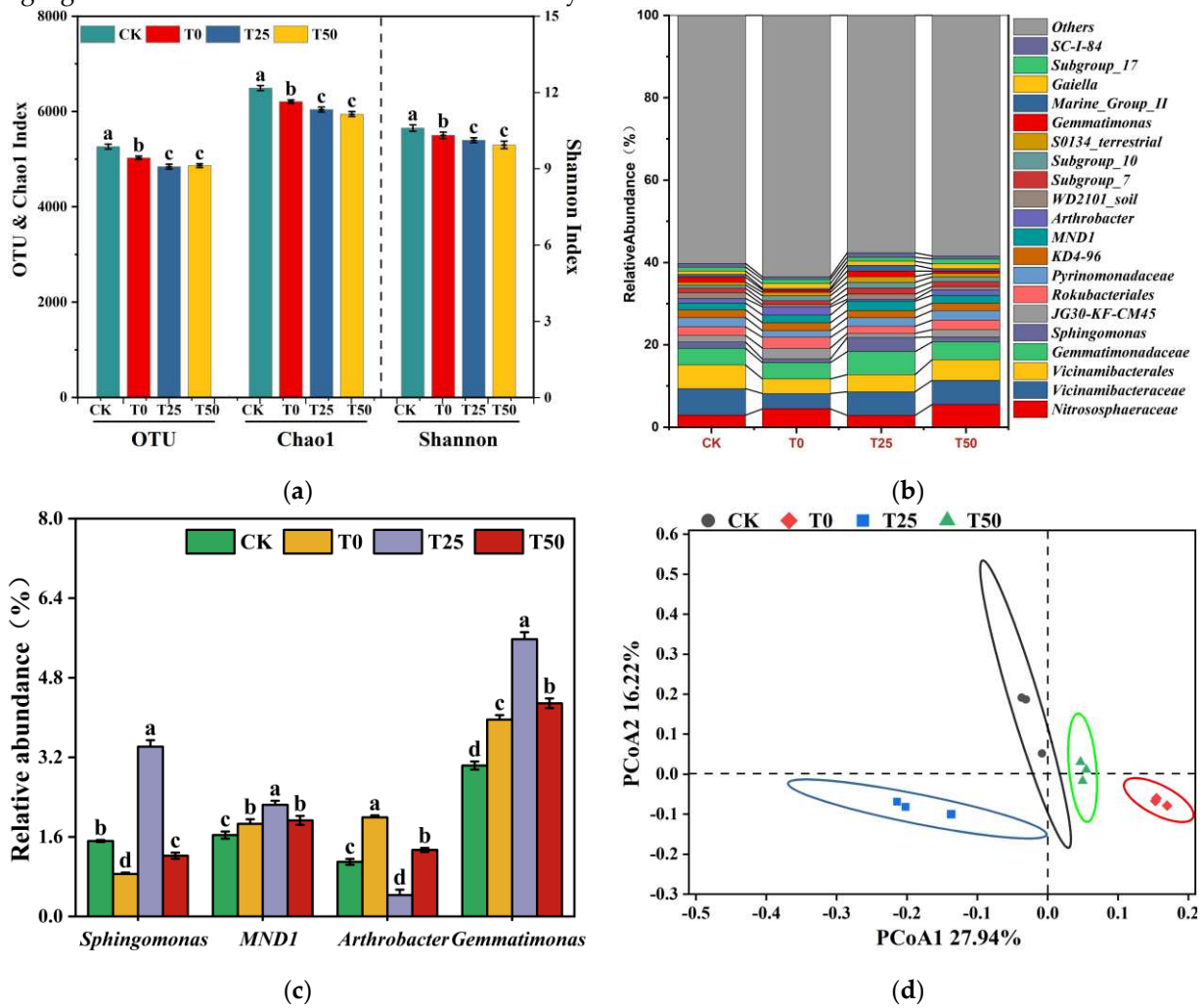


Figure 4. (a) Bacterial Operational Taxonomic Units (OTUs) and Indices (Chao1 Richness, Shannon Diversity). (b) Most Prevalent Bacterial Genera. (c) Functional Bacteria Abundance. (d) Principal component analysis (PCA) plot of bacteria

Fungal community structure. There were 2955 fungal OTUs (Figure 5-a), with differences in the number of OTUs among the different treatments: CK (782), T0 (749), T25 (717), and T50 (707). Compared to the CK treatment, the T0 treatment reduced fungal abundance by 4.36%, while the T25 and T50 treatments further reduced fungal abundance by 9.01% and 10.61%, respectively. Notably, the T25 and T50 treatments also decreased the fungal Shannon index and Chao1 index by 2.97%, 11.19%, and 25.63%, 15.89%, respectively.

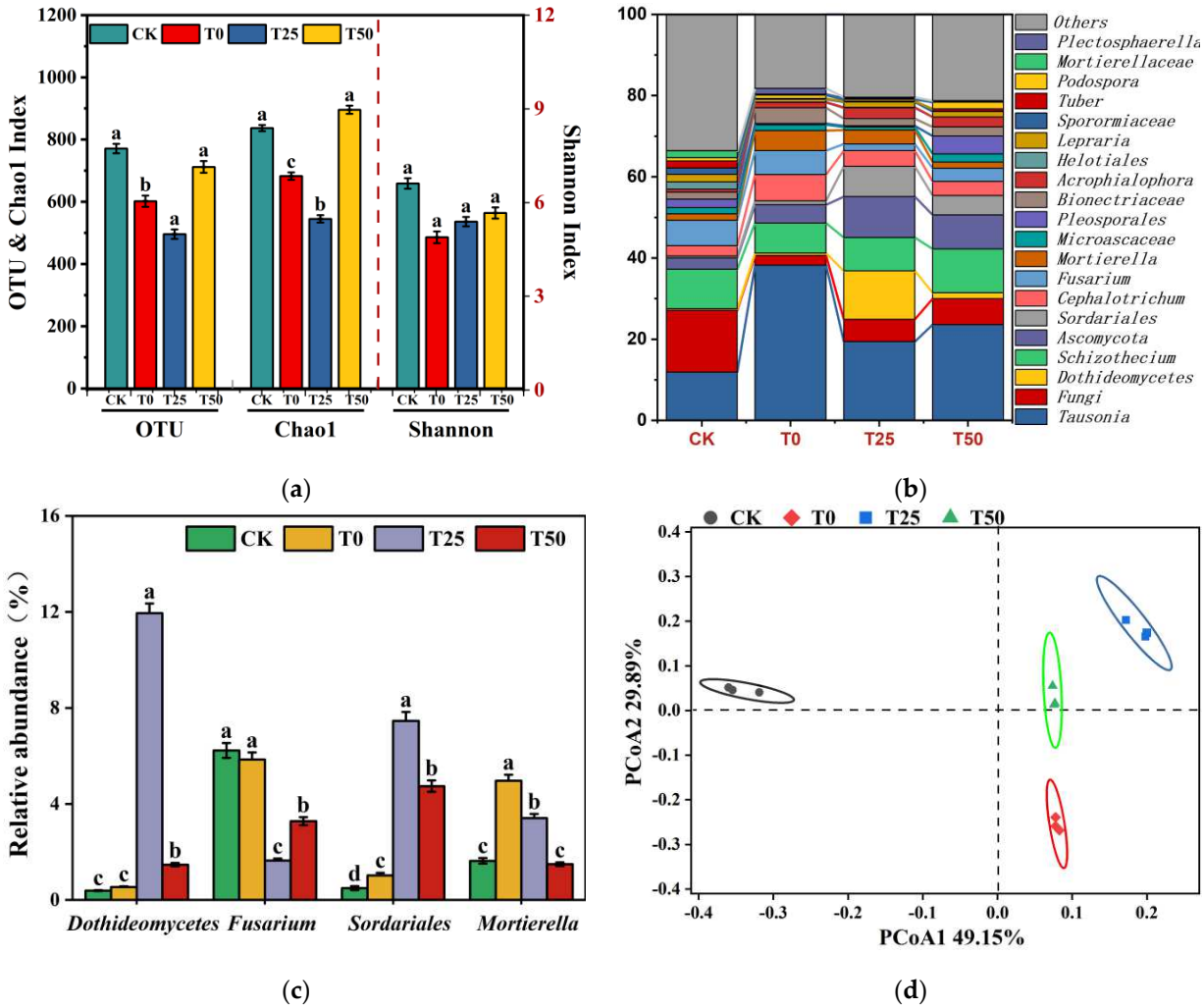


Figure 5. Soil microbial fungal community analysis. (**a**) Fungal OTU index, richness (Chao1), and diversity (Shannon) indices.; (**b**) Abundance of the top 20 fungal genera; (**c**) Functional fungal microorganisms; (**d**) Principal component analysis plot of fungi (PCoA).

At the fungal genus level (Figure 5-b), the top 20 genera accounted for 76.63±5.12% of the total sequences in the samples. Tausonia had the highest average relative abundance, reaching 23.27%, followed by Schizothecium (9.03%), Fungi_gen_Incertae_sedis (7.38%), Ascomycota (6.42%), and Fusarium (4.25%). Specifically, the T25 treatment significantly increased the abundance of Dothideomycetes, Ascomycota, Sordariales, and Mortierella by 11.95%, 10.06%, 7.46%, and 3.41%, respectively (Figure 5-c). In the T0 treatment, Tausonia had the highest relative abundance at 38.19%, significantly higher than in other treatments. Compared to the CK treatment, all treatments significantly increased the abundance of Mortierella and Fusarium, with increases of 6.3%-12.1% and 3.2%-5.1%, respectively. In contrast, the abundance of Fusarium was significantly reduced by 47.37%-73.59% in the T25 and T50 treatments.

Impact of Soil Factors and Functional Microorganisms on Maize Yield. *From the redundancy analysis (RDA) plots (Figures 5-a; 5-c), it is evident that different fertilization treatments have significant effects on soil quality, soil carbon storages, and microbial communities ($P < 0.05$). In the RDA plots for bacteria and fungi, the contributions of Axis 1 and Axis 2 were 19.08% and 13.98%, and 44.62% and 28.58%, respectively. The RDA1 axis primarily explains the variation in soil nutrients and microbial communities (Figure 5-b; 5-d).*

In the bacterial community, Sphingomonas, MND1, and Gemmatimonas were positively correlated with soil quality (SQI) and soil carbon storages. Additionally, Sphingomonas showed a significant correlation with SOC, MBC, and ROC, while Gemmatimonas was significantly positively correlated with DOC, yield, and SQI. In the fungal community, Mortierellaand Dothideomycetes were positively correlated with yield, SQI, and the organic carbon storage, whereas Fusarium showed a negative correlation with soil quality and carbon storages. Sordariales had a significant negative correlation with both yield and soil quality.

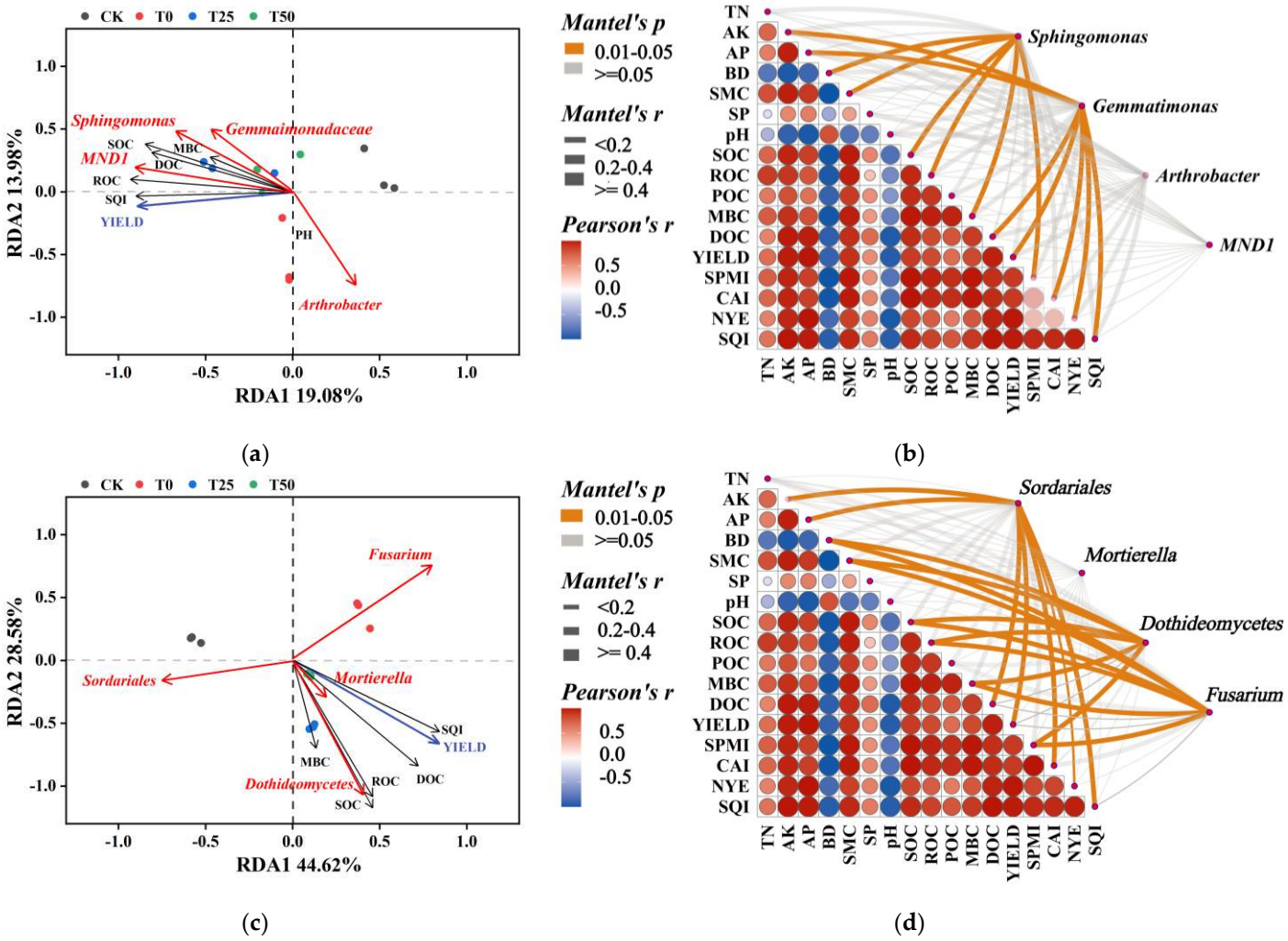


Figure 5. Soil Microbial Redundancy Analysis and Correlation Analysis (a) RDA ordination of the bacterial community; (b) Mantel test results for the bacterial community; (c) RDA ordination of the fungal community; (d) Mantel test results for the fungal community.

Discussion

Effects of organic fertilizer substitution on soil carbon storage

Soil organic carbon (SOC) is a key material basis for the stable storage and effective supply of soil nutrients, playing a crucial role in maintaining the functionality of soil ecosystems [30]. Soil organic carbon consists of multiple components, and there are significant differences in the content, transformation rates, and stability of these components. The impact of different fertilization treatments on these components directly or indirectly accelerates the input and transformation of soil organic carbon. Research indicates that the use of synthetic fertilizers typically boosts soil organic carbon levels by improving nutrient availability and optimizing soil conditions, thereby facilitating organic carbon retention. Notably, substituting chemical fertilizers with organic alternatives introduces supplementary organic carbon inputs, accelerating the breakdown and conversion of plant and animal matter. This process significantly enhances the soil's capacity to sequester organic carbon. The findings of this study demonstrate that fertilization practices markedly elevated concentrations of key carbon fractions, including SOC, ROC, POC, MBC, and DOC. Among these, the T25 organic fertilizer substitution treatment led to a striking 112.61% increase in POC levels compared to the control group (CK)—far surpassing the 21.17% rise observed with chemical fertilizers alone. This result aligns with earlier research, reinforcing the efficacy of organic amendments in carbon storage. [32]. This could be because POC not only binds with soil minerals (such as clay) to form stable organic-mineral complexes but also enhances the stability of soil organic carbon, allowing it to remain stable in the soil for a long time, reducing carbon loss and thereby enhancing soil carbon storage capacity [33]. DOC, as the most easily soluble form of organic carbon, accumulated the highest in the T25 treatment. Due to its high mobility and degradability, DOC can quickly enter the soil solution after the application of organic fertilizer, providing a direct carbon source for microorganisms. Although DOC can rapidly be converted

into microbial metabolic energy, due to its lower stability, it cannot accumulate in the soil over the long term [34]. Microbial biomass carbon (MBC) is the most active component of soil organic carbon [35], and the number of microorganisms directly affects the mineralization of soil organic matter and nutrient transformation efficiency [36]. MBC transformation is dominated by microbial assimilation and decomposition of organic carbon sources. This study revealed elevated microbial biomass carbon content following optimal organic fertilizer application, aligning with Chakraborty et al.'s findings.[35,37]. Microbial communities efficiently metabolize carbon sources, converting them into intracellular organic carbon and releasing carbon dioxide or transforming them into more stable organic carbon forms through decomposition. This process plays a crucial role in the dynamic cycling of soil carbon.

This study also found that with the increase in the organic fertilizer substitution ratio, the organic carbon content showed a declining trend. Although organic fertilizers provide abundant organic carbon sources to the soil, their decomposition rate is slow and uneven, limiting the stability of soil organic carbon. Similar results were observed in the experiments of Wang et al. [27]. When the organic fertilizer substitution ratio was too high (e.g., 50% organic fertilizer replacement), soil microbial communities may not be able to efficiently decompose and transform the excess organic carbon. Some carbon sources failed to form stable complexes with mineral surfaces, inhibiting microbial metabolic activities, causing the loss of organic carbon to exceed the accumulation rate.

Organic carbon that's readily broken down and utilized by critters in the dirt is what we're talking about when we refer to soil's active organic carbon. It's a big deal in understanding how carbon moves around in the soil. The more active organic carbon there is, the quicker the carbon storage in the dirt swaps out, and the livelier the carbon cycle becomes. Tracking shifts in the amount of active organic carbon can give us a clearer picture of the soil's health and its ability to keep carbon stored for the long haul, as indicated in reference [38]. This study found that the percentages of active organic carbon in SOC were POC > ROC > DOC > MBC, as POC can remain in the soil for a long time by binding with soil mineral particles. After organic fertilizer is applied to the soil, it combines with some sand particles, providing organic carbon components similar to POC [30]. Chemical fertilizers, when used in combination, can speed up the breakdown of external organic materials while simultaneously boosting the cycling of naturally occurring soil organic matter. As a result, this approach effectively enhances both the creation and conversion of particulate organic carbon in the soil. [39].

The differences in organic fertilizer substitution ratios in T25 and T50 treatments affected the proportion of active organic carbon in the soil. In the T25 treatment, POC and MBC had the highest proportions, while in the T50 treatment, ROC and DOC had the highest proportions. This may be because the T25 treatment provided an appropriate amount of organic carbon sources, allowing the soil's organic carbon dynamics to remain relatively balanced. Microorganisms not only decompose exogenous organic carbon but also maintain high POC and MBC proportions, efficiently decomposing organic matter and avoiding excessive carbon sources burdening microbial metabolism. In contrast to POC and MBC, ROC and DOC are easily decomposable organic substances with high activity and strong mobility, which can rapidly be converted into a stable carbon storage during microbial metabolism. The T50 treatment provided more carbon sources, and due to the slow-release nature of carbon sources in organic fertilizer, microorganisms tended to preferentially use and continuously decompose these easily decomposable organic carbon sources [40].

CPI and CPMI indices, as comprehensive indicators for assessing soil carbon management effects, can accurately monitor the impact of management measures on carbon storage and stability [41]. The CA and CAI indices are used to measure the conversion speed of carbon in soil and the microbial activity status, which can better observe the dynamic changes in soil carbon. According to different management measures, significant changes occurred in the content of soil organic carbon and active organic carbon components, leading to changes in the soil carbon storage management index [42]. In this experiment, the CPMI, CA, CPI, and CAI indices for each treatment group were ranked from high to low as follows: T25 > T50 > T0 > CK. The control group and the single chemical fertilizer treatment group showed lower values for these indicators due to the lack of organic fertilizer supplementation and fewer carbon sources in the soil. As the organic fertilizer substitution ratio increased, the indicators first increased and then decreased. This suggests that organic fertilizer substitution is more meaningful than chemical fertilizer alone for improving soil carbon storage management indices, and the effect of an appropriate organic fertilizer substitution ratio is more significant.

Effects of organic fertilizer substitution on soil properties and maize yield

The Soil Quality Index (SQI) is a multidimensional indicator used to assess soil health and productivity [43]. Based on the composite method of Dai, which processes 16 soil quality-related indicators, the SQI under the T25 treatment was

significantly higher than that under the T0 treatment. The substitution of chemical fertilizers with organic fertilizers significantly improved the overall soil quality. However, there were no significant differences in soil bulk density and total porosity between the organic fertilizer substitution treatments and the chemical fertilizer-only treatment, a phenomenon consistent with findings from Dong Chunyu's research [44]. This can be attributed to the fact that changes in soil physical properties generally require a longer period of accumulation. While organic fertilizers work wonders for enhancing soil composition, boosting organic carbon levels, and stimulating beneficial microbial life, their effects on soil bulk density and porosity don't happen overnight. It takes time for these amendments to truly make their mark, as the initial rise in organic matter and aggregate formation hasn't yet reached a critical threshold where substantial changes to soil density and porosity would become apparent [45].

After the application of organic fertilizer as a substitute for chemical fertilizers, The soil pH was notably diminished compared to the group that solely received chemical fertilizer. This change was primarily due to the microbial metabolic activities during organic fertilizer decomposition. Soil microorganisms release ammonia and hydroxide ions when decomposing organic matter, which can neutralize hydrogen ions in the soil, thus alleviating soil acidification. Additionally, alkaline cations such as calcium and potassium in organic fertilizers further neutralize soil acidity during ion exchange with soil hydrogen ions, lowering soil pH and improving the soil's acid-base balance [46]. This process not only helps mitigate acidification caused by excessive fertilizer use but also increases the availability of soil nutrients, promoting microbial activity and providing a more favorable environment for soil health. Akhtar et al. (2018) found that compared to chemical fertilizers alone, the combined application of chemical fertilizers with organic manure and straw significantly increased the accumulation of soil nutrients like nitrogen, phosphorus, and potassium. Compared to traditional methods that depend entirely on synthetic fertilizers, using organic amendments resulted in significantly higher levels of total nitrogen (TN), available phosphorus (AP), and available potassium (AK) in the soil. The difference wasn't subtle—organic inputs clearly outperformed their chemical counterparts in enriching the soil's nutrient profile [42]. This phenomenon can be attributed to the fact that organic amendments enhance both the physical structure of the soil and the efficiency of nutrient conversion processes. Through the mechanisms of dissolved organic matter and direct nutrient provision, these organic materials facilitate the effective buildup of essential nutrients within the soil profile. [47].

In this study, significant improvements in plant growth parameters, such as plant height, stem diameter, leaf area index, ear length, and hundred-grain weight, were observed within the same fertilizer treatment group, laying a foundation for increased maize yield. The T25 and T50 organic fertilizer treatments significantly increased maize yield by 24.13%-28.48% compared to conventional fertilization. At the same time, nitrogen use efficiency, agronomic nitrogen efficiency, and nitrogen partial productivity were also significantly higher than those in the chemical fertilizer-only treatment group. These findings are consistent with Xu Chunyan's conclusions [48]. This is due to two primary causes: first, the use of organic fertilizers boosts soil carbon and enhances microbial activity and nutrient transformation effectiveness.. The rich carbon sources are decomposed by microorganisms, releasing nutrients and generating humus and organic acids, which not only optimize the soil's cation exchange capacity but also enhance the soil's water retention and gas exchange functions, thereby improving overall soil fertility [49]. On the other hand, the nitrogen sources in organic fertilizers have a slow-release characteristic, providing a continuous nitrogen supply, preventing nitrogen loss and fixation, optimizing the nitrogen cycle, and effectively improving nitrogen utilization efficiency. This ensures that maize receives sufficient nutrients throughout its growth cycle, promoting growth and increased yield.

Effects of organic fertilizer substitution on soil microbial community structure

Soil microorganisms serve as the backbone of nutrient cycling within the earth, playing an indispensable part in preserving soil health and fueling plant development. These tiny powerhouses break down organic materials and convert nutrients found in the soil, effectively managing the buildup, preservation, and depletion of vital elements like carbon, nitrogen, and phosphorus. In doing so, they directly shape soil fertility and determine how well maize and other crops can flourish [50,51]. Research indicates that the variety of microorganisms in the soil is a key factor in gauging its quality and productivity [52]. Prolonged use of chemical fertilizers can actually squash the diversity of soil bacteria. [53,54], but the appropriate application of organic fertilizers can effectively alleviate this negative impact by improving the structure and spatial distribution of the soil microbial community, thereby promoting soil health [55].

The results of this study showed that, compared to the control group, the fertilized treatment groups exhibited increases in OTU, Shannon, and Chao1 indices, with bacterial diversity improving [56,57]. Conversely, fungal micro-

organisms showed a significant decline [58], the results align with those of Song's investigation [59]. This could be due to the impact of using either chemical or organic fertilizers on the soil's nutrient equilibrium. Although the increased carbon and nitrogen sources provide favorable conditions for microbial growth, they also increase competition between microorganisms. Fungal microorganisms, due to their slower metabolic rate in decomposing complex organic matter and their higher sensitivity to environmental changes [60], often cannot quickly adapt to changes in nutrient availability. As bacterial communities, especially decomposer bacteria, gain dominance, their rapid nutrient uptake and conversion capabilities enable them to outcompete fungi, inhibiting fungal growth and reproduction [61]. Notably, when organic fertilizers replace chemical fertilizers, this decline in fungal abundance becomes more pronounced. This could be due to the introduction of new organic nutrients and exogenous microorganisms from the organic fertilizers, which alter soil environmental factors and either promote or inhibit the growth of certain microbial populations.

Fungi are of great interest due to their role in decomposing plant residues and organic matter. The abundance of genera such as Dothideomycetes, Tausonia, Sordariales, and Mortierella significantly increased, likely because the application of organic fertilizers greatly enhanced the organic carbon sources in the soil, providing abundant nutrients for these fungi [62]. Organic fertilizers can activate specific microbial communities (e.g., decomposers) by increasing soluble carbon sources in the soil, accelerating the decomposition of organic matter. This finding aligns with Yang's research [63], which showed that organic fertilizer application promotes the growth of decomposer microbes such as Tausonia and Mortierella. These fungi break down lignin, cellulose, and other complex organic substances in plant residues, releasing nutrients that are available for plant absorption, thereby improving soil fertility. In the T25 treatment, the abundance of Mortierella increased most significantly, likely because Mortierella, a common decomposer microorganism, accelerates the breakdown of complex organic substances through enzyme secretion, enhancing the nutrient release rate in the soil and providing the nutrients required by plants.

On the flip side, the prevalence of Fusarium took a nosedive [64], and statistical analysis revealed it was inversely proportional to corn production. This trend likely stems from the shake-up in the soil's microbial makeup triggered by the use of organic fertilizers. Studies have shown that fungi such as Mortierella and Tausonia exhibit strong pathogenic resistance in the soil. These beneficial microorganisms can suppress the expansion of pathogens like Fusarium by competitive exclusion or antimicrobial substance production [65].

The relationship between soil quality, soil organic carbon storage, and functional microbial communities

In modern agriculture, interactions among soil quality, microbial communities, organic carbon storages, and maize yield create a dynamic ecological cycle. Soil organic carbon storages are the foundation of soil fertility, and their stock directly impacts the construction and function of microbial communities. The spatial redistribution of different reactive carbon components (such as POC, ROC, DOC, and MBC) determines the soil's ability to process and convert carbon, which contributes to the formation of redox microzones. These microzones regulate enzyme-substrate contact probabilities through the "open/close" effect, directly influencing "how much carbon" can be converted into "how much carbon available for microbial processing," thereby affecting soil quality and crop productivity. Recent research has demonstrated that swapping out chemical fertilizers for organic ones not only leads to a substantial rise in the soil's carbon reserves, but it also fuels a lively growth of microorganisms due to the constant supply of carbon, promoting improvements in soil quality. Under the influence of microbial communities, organic carbon in the soil is converted into plant-absorbable nutrients through organic matter decomposition, thereby driving nutrient cycling and transformation, significantly enhancing soil fertility and crop growth potential [66].

The improvement in soil quality is the most direct feedback from organic fertilizer application, manifested in increased cation exchange capacity (CEC), enhanced water retention capacity, and improved pore connectivity. These structural changes in the soil not only improve its physical properties, making it more suitable for plant root growth, but also enhance nutrient retention capacity, reducing the loss of water and nutrients, thereby promoting maize growth efficiency [67]. From the perspective of microbial communities, groups such as Sordariales exhibited significant positive correlations, particularly in the relationships between soil quality, soil organic carbon storages, and crop yield. These microorganisms effectively decompose aromatic compounds and semi-stable substrates, releasing buried nutrients like nitrogen and phosphorus, thereby significantly improving nutrient mineralization and assimilation efficiency. Microbial communities optimize nutrient release and promote soil quality improvement, not only enhancing nutrient absorption capacity in crops but also boosting crop growth potential.

The interaction between soil organic carbon storages and microbial communities plays a core role in the process of organic fertilizer substitution for chemical fertilizers. Microbial communities significantly improve crop yield by optimizing nutrient release, promoting soil quality improvement, and enhancing nutrient absorption efficiency in crops. Specifically, when it comes to bacterial ecosystems, particularly those microorganisms that participate in nitrogen recycling like ammonia-oxidizing and denitrifying bugs like MND1, they are super sensitive to shifts in soil conditions. These critters are like the unsung heroes of nutrient, soil vigor, and the success of our crops. Additionally, while fungal communities typically respond more slowly to environmental changes, they still play an indispensable role in decomposing resistant organic matter and stabilizing soil organic matter. Fungal genera, especially decomposers like Mortierella and Tausonia, significantly increase in soils where organic fertilizers are applied, consistent with Yang's experimental results [68]. These fungi break down lignin, cellulose, and other resistant organic substances in plant residues, releasing nutrients that can be absorbed by plants, thereby improving soil fertility and crop yield.

Microbial ecosystems significantly impact nutrient recycling and the increase of agricultural productivity, particularly during the shift from inorganic to organic soil amendments. This dominance becomes even more pronounced in such treatments. Bacterial communities, especially decomposer groups, accelerate nutrient absorption and transformation through their dominant presence in the soil, and inhibit fungal growth and reproduction through competitive interactions. In this process, the abundance of pathogens such as Fusarium significantly decreases, showing a significant negative correlation with maize yield. This phenomenon is likely closely related to changes in microbial community structure. Studies have shown that fungi such as Mortierella and Tausonia possess strong pathogen resistance in the soil. These beneficial microorganisms can exclude or suppress the expansion of pathogens like Fusarium, providing a healthier environment for crop growth [65].

Overall, the diversity and functionality of microbial communities in the process of organic fertilizer substitution for chemical fertilizers not only improve soil quality but also increase nutrient transformation efficiency, thereby promoting crop growth and yield. The interactions and complementary functions between bacterial and fungal communities provide a solid foundation for enhancing soil quality, thus offering an effective path for achieving sustainable agricultural development.

Conclusions

In summary, this study reveals the synergistic effect of the organic fertilizer substitution strategy for reduced chemical fertilizer use, achieving significant improvements in soil fertility, microbial diversity, and maize yield. The results indicate that, compared to the chemical fertilizer-only group, organic fertilizer substitution for chemical fertilizers effectively enhanced the soil organic carbon storage by increasing carbon sources, while improving soil water retention and structural stability. At the same time, it regulated the physical, chemical, and biological properties of the soil, resulting in improvements in soil quality and microbial community structure. Notably, substituting 25% of chemical fertilizer with organic fertilizer produced more significant effects than substituting 50%. Moreover, the synergistic interaction between the soil organic carbon storage, soil quality, and functional microbial communities is the key driving force for increased maize yield. These findings provide a scientific basis for sustainable agricultural development and contribute to promoting the application of organic fertilizer substitution for chemical fertilizers as a green agricultural strategy.

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