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Appropriate Application of Organic Fertilizer Can Effectively Improve Soil Environment and Increase Maize Yield in Loess Plateau

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Abstract: Fertilization has a significant impact on soil nutrients and microbiological properties, which, in turn, affect crop yield. However, the specific effects of organic and inorganic fertilizers on soil fertility and microbial characteristics in maize fields, as well as the key soil factors influencing changes in crop yield, remain largely unknown. A study was conducted over two years (2021–2022) to investigate the impact of various nitrogen fertilization rates and types on maize yield and soil properties in the Loess Plateau. Field experiments with five nitrogen levels (60, 90, 120, 150, and 180 kg N ha^{-1}) and two fertilizer types (chemical and organic) were conducted. The optimal yield was achieved with 150 kg N ha^{-1}, significantly surpassing that of other treatments by 4.5−45.7%. Compared with the organic fertilizers, the chemical fertilizers increased soil salt and catalase levels, with soil nitrate and ammonium content being higher at the jointing stage but lower at maturity. Organic fertilization improved soil potassium, organic matter, urease and phosphatase activities, and microbial populations. Yield correlated with several soil indicators, including salt content, nitrate, available potassium, and enzyme activities. Notably, soil nitrate also correlated with actinomyces quantity. A principal component analysis showed that the organic fertilizer was more beneficial to soil health than the chemical fertilizer. Consequently, this study recommends 150 kg N ha^{-1} of organic fertilizer for sustainable maize farming and soil health in China's northwest arid region, providing a theoretical framework for agricultural practices.

Keywords: effectiveness of fertilizer; organic fertilizer; soil health; correlation analysis; soil microbiological properties

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1. Introduction

To ensure stable and sustainable crop production for a growing population, it is essential to have healthy farmland soils. However, agricultural productivity in the Loess Plateau is declining due to severe vegetation degradation, drought, and soil erosion [1]. Fertilization plays a crucial role in enhancing crop yield potential and soil fertility [2]. Excessive inorganic fertilizer use in field production systems often leads to low crop nutrient use efficiency [3]. To maintain crop yield and soil fertility, fertilizer input should exceed crop absorption levels [4]. The goal of fertilization is to adjust soil nutrients to increase yields and enhance nutrient absorption and utilization by crops, ultimately maintaining soil fertility balance [5–7].

With defined parameters, the accumulation of nitrogen in the superior zone of maize cultivation increases with alterations in nitrogen fertilization [8]. The over-application of nitrogen causes an increase in soil depletion and nitrogen residues [9]. A minimal fraction of soil-resident nitrogen is assimilated by crops, while the majority undergoes unproductive dissipation [10]. Excessive nitrogen inputs reduced nitrogen recuperation, recirculation, and the crop yield increases [11]. The prolonged employment of synthetic fertilizers causes a decline in soil microbial diversity and soil acidification, and it impairs the soil's ecological resilience [12].

Organic fertilization alters soil carbon and nitrogen availability, enhances microbial activity, and markedly increases enzymatic activity [13]. It boosts soil microbial biomass, ameliorates rhizosphere microbial communities, and increases microbial diversity and soil enzyme function [14]. Numerous studies have assessed the impact of fertilization strategies on soil enzyme activity, particularly contrasting organic with inorganic fertilizers [15–17], often revealing that their combination enhances soil fertility and enzyme activity. Despite the prominence of organic fertilizers in agronomic research, studies exploring the effects of the combined use of organic and inorganic fertilizers on soil enzymatic functions and physicochemical properties through maize's growth stages, specifically in the Loess Plateau, remain scarce.

Soil nitrogen cycling is integral to nutrient availability, with inorganic fertilizers influencing soil nitrification and denitrification processes [18]. Denitrification, predominantly facilitated by heterotrophic facultative anaerobes, involves nitrate reduction to nitrogen gas under anaerobic conditions [19]. Incomplete denitrification can emit nitrogen oxides, contributing to nitrogen nutrient loss [20]. Integrating organic modifications with fertilizers is acknowledged as an effective strategy for increasing short-term yields and long-term soil organic content [21]. Long-term organic fertilization studies suggest its potential to enhance yields and soil organic matter, aligning with sustainable development objectives. Organic fertilizers enrich the soil's microbial nutrient structure and increase microbial biomass carbon and nitrogen, aiding the conversion of nutrients from organic fertilizers into stable organic matter. Previous studies found that the long-term application of organic fertilizer significantly increased soil organic matter and enhanced microbial diversity on the Loess Plateau [1]. This leads to improvements in soil structure and aeration, which are critical for maize root development and nutrient uptake [16,17]. In addition, a balanced supply of micronutrients and macronutrients from organic fertilizers has been shown to promote healthier plant growth and resilience to environmental stresses, ultimately leading to sustained increases in corn yields over many years compared to plots using inorganic fertilizers.

In northern Shaanxi's arid regions, the overuse of inorganic fertilizers can induce soil acidification, compaction, and degradation, consequently decreasing crop yields, jeopardizing agricultural product safety, and causing ecological concerns. Organic fertilizers can equilibrate soil microbial flora, optimize rhizosphere microecology, and reinstate the soil's self-purifying capabilities. Although the impact of organic fertilizers on maize yield is notably positive, comparative studies between the effects of organic and inorganic fertilizers on maize in the Loess Plateau are limited. This study assesses how different nitrogen fertilizer type and application rates affect soil enzymes, soil nutrients, and maize yields in the Loess Plateau. The purpose of this study is to provide a scientific basis for the optimization of nitrogen fertilizer dosage and fertilizer type for maize production in the Loess Plateau area.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted during the maize growing season in 2021 and 2022 in the common farmland of Gaoqiao Town, Ansai District, Yan'an City, Shaanxi Province (E 109°11′, N 36°39′). The region has a semi-arid monsoon climate and is in the middle and temperate continental zone, with an altitude of 1371.9 m. The average annual temperature is 8.8 °C, and the average annual precipitation is 505.3 mm. The precipitation is mainly concentrated from July to September, the annual sunshine duration reaches 2395.6 h, and the frost-free period lasts for 157 days throughout the year.

A rainfall recorder (Beijing East West Instrument Technology Co., Ltd. WI92859, Beijing, China) was used to measure the precipitation of each rainfall event station in each growth period and to calculate the annual precipitation. The total precipitation in

2021 and 2022 was 627 mm and 529 mm, respectively (Figure S1), but the distribution varied considerably between the two years. The total precipitation of the 2021 and 2022 maize growing seasons was 512 mm and 479 mm, respectively. According to the USDA Soil Classification System, the test site soil is sandy loam (limestone formation). Before the experiment, the bulk density of cultivated soil (0–60 cm) was 1.4 g cm^{-3}, the field water capacity was 22.1%, the soil pH was 8.4 (soil–water ratio of 1:5), the soil ammonium nitrogen content was 5.34 mg kg^{-1}, and the soil nitrate nitrogen content was 7.87 mg kg^{-1}. The soil available phosphorus content was 12.12 mg kg^{-1}, and the soil available potassium content was 33.45 mg kg^{-1}.

2.2. Experimental Design

The maize variety tested was 'Zhengdan 958', and the fertilizers tested were urea (N, 46%), superphosphate (P_2O_5, 12%), potassium sulfate (K_2O, 52%), and organic fertilizer (mainly sheep manure, total nutrient $\geq$ 5%). A randomized complete block design with two factors and three replications was arranged. Five nitrogen fertilizer application rates (60 kg N ha^{-1}, 90 kg N ha^{-1}, 120 kg N ha^{-1}, 150 kg N ha^{-1}, and 180 kg N ha^{-1}) and two nitrogen fertilizer types (chemical fertilizer and organic fertilizer) were applied in 2021 and 2022. The chemical nitrogen application methods were base fertilizer (half of the total fertilizer application) and topdressing fertilizer (half of the total fertilizer fertilizer application). The base fertilizer (phosphate fertilizer: 120 kg ha^{-1}; potassium: 200 kg ha^{-1}) was applied before planting. Topdressing was performed at the end of June. The chemical nitrogen application consisted of five treatments: N1 (60 kg ha^{-1}), N2 (90 kg ha^{-1}), N3 (120 kg ha^{-1}), N4 (150 kg ha^{-1}), and N5 (180 kg ha^{-1}). The organic fertilizer was applied as the base fertilizer, which was applied in each treatment at the same time. The organic nitrogen application consisted of five treatments: TN1 (60 kg ha^{-1}), TN2 (90 kg ha^{-1}), TN3 (120 kg ha^{-1}), TN4 (150 kg ha^{-1}), and TN5 (180 kg ha^{-1}). In this experiment, the maize row spacing was 60 cm, and the plant spacing was 25 cm. Each plot was 10 m long and 6 m wide (10 m $\times$ 6 m = 60 m^2). The control group (CK) was treated without fertilization. A total of 11 plots were set up, with a total area of 660 m^2.

The experiments were conducted in two maize growing seasons, 2021 and 2022. The maize was sown on 5 May 2021 and 6 May 2022. The maize growth period lasted for 161 days in 2021 (the harvest date was 13 October) and 162 days in 2020 (the harvest date was 15 October). The traditional local row planting method was adopted, with a single row layout, a row spacing of 90 cm, and a planting distance of 20 cm. Nine rows of maize were planted in each plot at a density of 50,000 plants ha^{-1}. The experimental design was the same for both years. There was no irrigation throughout the growing period.

Urea, ammonium dihydrogen phosphate, and potassium chloride were applied as fertilizers twice throughout the growing season. Half of the total nitrogen fertilizer was used as the base fertilizer and applied to the soil before the maize was sown. The other half was used as topdressing and applied to different treatment experimental plots 60 days after sowing.

2.3. Measurements and Calculations

2.3.1. Plant Height, Leaf Area Index, and Dry Matter Accumulation

A tape measure was used to measure the height of the maize. Maize plant height was measured 4 times for each treatment at different growth stages (seedling stage (JS, 7-leaf stage), jointing stage (TS, 14-leaf stage), silking stage (SS, silks visible outside the husks), and physiological maturity stage (MS, approximately 50 days after the filling stage)).

The length (L, cm) and maximum width (W, cm) of each green leaf of the selected plant (3 plants) were determined, and the following formula was used to calculate the leaf area per plant.

$$LA = \sum(L \times W) \times 0.7 \quad (1)$$

where LA is the leaf area of a single plant (cm^2), L is the leaf length (cm), W is the maximum leaf width (cm), and 0.7 is the conversion factor of the leaf area of a single plant.

Three plants were randomly selected from each plot for DMA determination. After washing off the soil, the roots, leaves, stems, and tubers were placed in an oven at 105 °C for 30 min and dried at 75 °C to a constant weight. The average dry weight of the total dry matter accumulation per hectare was calculated by multiplying 3 plants by planting density (plant ha^{-1}).

2.3.2. Grain Yield

The sampled plants were cut at ground level and divided into stems (including sheaths, stems, and bracts), leaves, cobs, and seeds. In each plot, all plants of the adjacent two rows of maize (excluding the rows sampled during the silk stage of the maize) were randomly selected and cut off at ground level, and all parts were counted before drying to a constant weight in a 75 °C oven. Ten ears were randomly selected from each plot, and the following yield components were measured: the number of spikes, the number of grains per spike, and the 1000-grain weight.

2.3.3. Soil Physical, Chemical, and Biological Indicators

The soil water content (SWC) was measured 4 times (at the seedling stage, jointing stage, silking stage, and physiological maturity stage) a year using the weighing method. The soil water content in the 0–100 cm layers was measured every 20 cm (161 DAS in 2021 and 162 DAS in 2022) 3 days before sowing and at the end of the harvest. Other soil water samples were measured in the 0–20 cm, 20–40 cm, and 40–60 cm soil layers. Soil electrical conductivity (SEC) was measured using a lightning magnetic portable conductivity meter (Fisher Scientific, Hampton, NH, USA). The soil salt content (SSC) was calculated as follows:

$$SSC = 3.47 \times SEC + 0.015 \quad (2)$$

where SSC is the soil salt content (‰), and SEC is the soil electrical conductivity (ms cm^{-1}).

Soil samples were collected from each plot using a soil auger (inner diameter 4 cm, TC-300B, Changzhi, China). This was replaced 3 times per treatment. After collecting the soil samples from the field, they were dried to a constant weight at 105 °C.

Other soil indicators were measured at the maize silking and maturity stages across the two years. Soil samples were collected with a soil auger for each treatment. During the collection of plant samples, 3 replicates were set in the 0–60 cm soil layer. The soil sample was divided into two parts. The first part (fresh soil) was used to analyze the soil microbial community, screened immediately on a 1 mm screen, and kept at 4 °C for half a month until analysis. The second part of the soil sample was used for the analysis of soil enzyme activity and the physicochemical index.

The soil microbial population was analyzed using the standard culture method. First, 10 g soil samples from each plot were weighed and then diluted with sterile distilled water at 1:10 in 250 mL heat-resistant glass bottles. Second, the samples were mixed for 25 min using a half-speed magnetic stirrer. Third, the 0.5 mL suspension was diluted into a 10-fold series and placed in a 20 mL test tube containing 4.5 mL sterile distilled water. Fourth, each diluent was inoculated with 4 Petri dishes containing 20 mL of a solid medium. After preparation, the number of bacteria was determined using the peptone broth plate counting method (colony-forming unit (CFU) g^{-1}). The Martin broth medium (CFU g^{-1}) plate counting method was used to analyze the number of fungi. The number of actinomycetes was determined using the starch ammonium salt medium (CFU g^{-1}) plate counting method.

Soil catalase activity (SCA) was determined via the reverse titration of a residual hydrogen peroxide solution and potassium permanganate solution. Soil urease activity (SUA) was determined using the indole blue method. Soil sucrase activity (SCA) was determined using the colorimetric method with a 3, 5-dinitrosalicylic acid reagent. Soil phosphatase activity (SCA) was determined via phenylate disodium phosphate colorimetry.

The soil nitrate nitrogen content (SNNC) and soil ammonium nitrogen content (soil ammonium nitrogen content) were extracted using 2 mol L^{-1} potassium chloride and indole blue colorimetry with a spectrophotometer (UV-2600, Shanghai Hengping Scientific Instrument Co., Ltd., Shanghai, China). The soil available potassium content (K) was extracted with ammonium acetate via flame spectrophotometry. Soil alkali-hydrolyzed nitrogen (SHNC) was determined via conductometric titration. Soil pH was measured with glass electrode pH meter (Horiba F-71S, Kyoto, Japan) (soil: water, 1:2.5). The soil organic matter (SOM) content was determined via the potassium dichromate volumetric method (external heating method).

2.4. Data Analysis

The study adopted a principal component analysis (PCA) to comprehensively evaluate soil physical, chemical, and biological indicators over a two-year period. The first step was data standardization. The original data were standardized to ensure that each variable had the same scale, avoiding the influence of variable differences on the principal components. The second step was to calculate the covariance matrix. The covariance matrix, which represents the correlations between variables, was calculated from the normalized data. The third step was eigenvalue decomposition. Eigenvalues and eigenvectors were obtained by performing eigenvalue decomposition on the covariance matrix. The fourth step was to select the number of principal components. The number of principal components to be retained was determined based on the magnitude of the eigenvalues, typically by selecting those with eigenvalues greater than a certain threshold or those accounting for a specific proportion of the total variance. The fifth step was linear transformation. The original data were transformed into principal components by multiplying them by with the eigenvectors. The sixth step was data reconstruction. The principal components were multiplied by the transpose of the eigenvectors and added to the mean vector to restore the data to the original space.

An analysis of variance was conducted to evaluate the effects of the different fertilizer types and rates on the parameters under study. Significant differences between the examined parameters were compared using Tukey's honest significant difference (HSD) test at the 95% confidence level ($p < 0.05$). In addition, the effects of fertilizer type and rate on the relationships among all the parameters were calculated using a bivariate correlation analysis (Pearson correlation coefficients and a two-tailed test of significance).

3. Results

3.1. Plant Growth Index and Grain Yield

The plant height, stem diameter, leaf area, and dry matter accumulation first increased and then decreased throughout the whole growth stage (Figure 1). There were no significant differences in the plant growth indices, with no significant differences among all treatments in the seedling stage (Tables S1–S4). When using the average nitrogen fertilizer application rate, the plant height obtained with the inorganic fertilizer was higher than that obtained with the organic fertilizer at the jointing and filling stages, and it was lower at the maturing stage (Table S1). The dry matter accumulation showed a similar trend, but the stem diameter and leaf area showed the opposite trend (Tables S2–S4). Grain yield increased with the increase in the N fertilizer application rate, and the effect of the N fertilizer application rate on yield was significant (Figure 2). There was a significant (R^2, 0.74–0.93) open downward parabolic relationship between grain yield and the N fertilizer application rate in both years (Figure S2). The grain yield of the N4 and TN4 treatments was the highest, being 4.5–41.6% higher than that of the other treatments in 2021 and 10.8–45.7% higher than that of other treatments in 2022 (Figure 2).

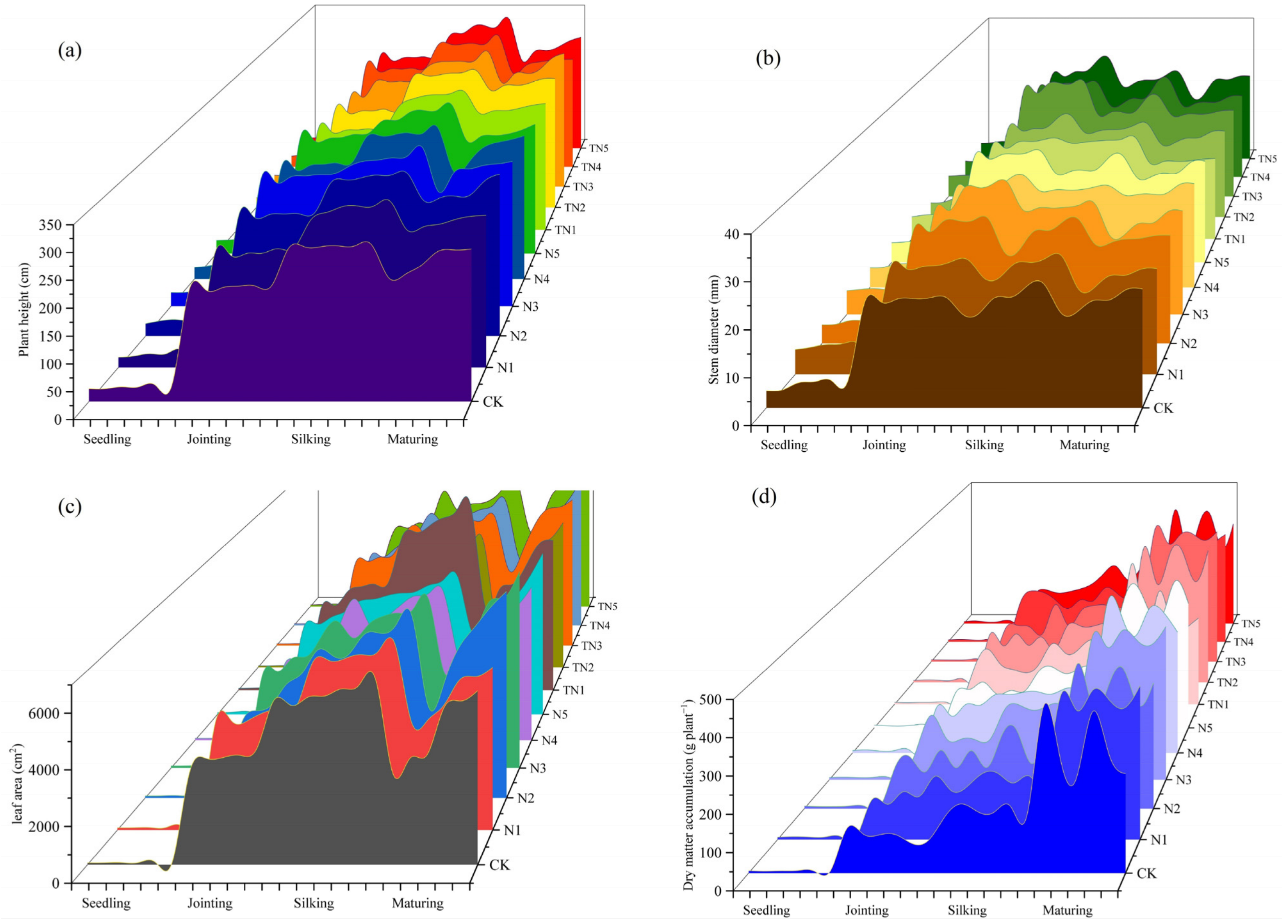

Figure 1. The mean plant height (**a**), stem diameter (**b**), leaf area (**c**), and dry matter accumulation (**d**) were affected by the different fertilizer types and application rates. Note: CK, without fertilization; N1, chemical fertilizer with 60 kg N ha^{-1}; N2, chemical fertilizer with 90 kg N ha^{-1}; N3, chemical fertilizer with 120 kg N ha^{-1}; N4, chemical fertilizer with 150 kg N ha^{-1}; N5, chemical fertilizer with 180 kg N ha^{-1}; TN1, organic fertilizer with 60 kg N ha^{-1}; TN2, organic fertilizer with 90 kg N ha^{-1}; TN3, organic fertilizer with 120 kg N ha^{-1}; TN4, organic fertilizer with 150 kg N ha^{-1}; TN5, organic fertilizer with 180 kg N ha^{-1}. The same below.

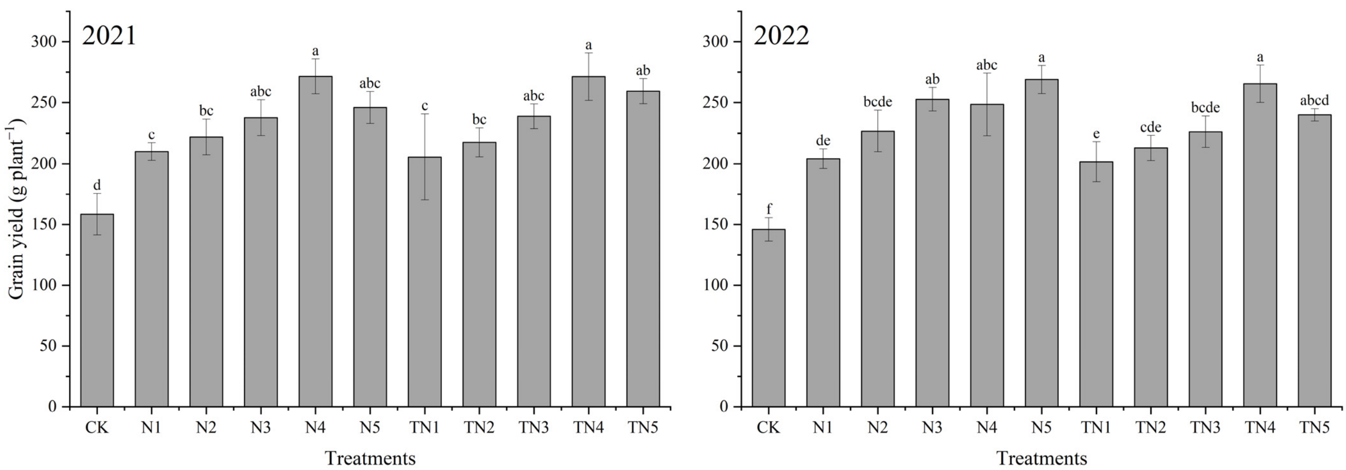

Figure 2. Grain yield obtained with the different fertilizer types and application rates in 2021 and 2022. Note: Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the HSD test. Each value is the mean ± SD (n = 3).

3.2. Soil Physical and Chemical Indicators

The soil water content obtained with the organic fertilizer was more stable than that obtained with the inorganic fertilizer (Figure 3a). The average soil water content under the N5 treatment was slightly lower than that under the other treatments (Figure 3a). The soil water content in the jointing stage decreased with the increase in soil depth, and the soil water content in silking and maturing stages showed the opposite trend (Table S5). According to the average fertilizer type and application rate, the soil water content at 0–20 cm was 29.7% and 42.6% higher than that at 20–40 cm, and 49.1% and 40% higher than that at 40–60 cm in 2021 and 2022, respectively (Table S5). There was no significant difference in soil pH among all the treatments (Figure 3b; Table S6). Soil pH increased with the increase in the soil depth at the jointing stage, but there was no obvious distribution law in the other growth stages (Table S6). On average, the pH value of CK was 1.12–4.85% higher than that of the other treatments (Table S6).

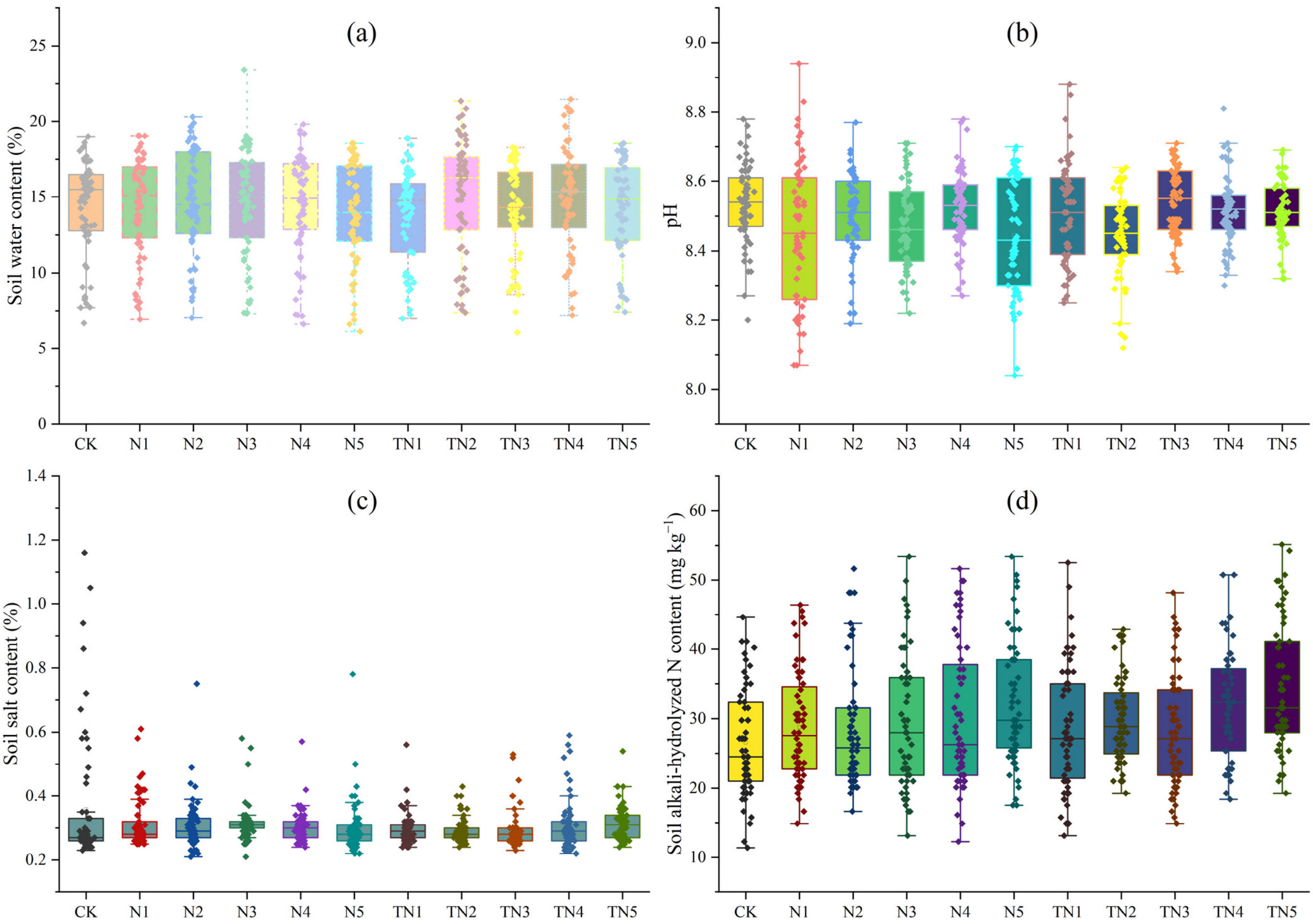

Figure 3. The mean soil water content (**a**), pH (**b**), soil salt content (**c**), and soil alkali-hydrolyzable nitrogen content (**d**) were affected by the different fertilizer types and application rates.

The soil salt content gradually decreased and tended to be stable as the maize growth period progressed (Figure 3c; Table S7). According to the average fertilizer type and application rate, the soil salt content at 0–20 cm was 32.2% and 33.9% higher than that at 20–40 cm, and 44.2% and 34.5% higher than that at 40–60 cm at the jointing stage in 2021 and 2022, respectively (Table S7). When using the average fertilizer application rate, the soil salt content obtained with the chemical fertilizer was slightly higher than that obtained with the organic fertilizer throughout the whole growth period (Table S7). The soil alkali-hydrolyzable nitrogen content increased with the increase in the fertilizer application rate (Figure 3d). According to the average fertilizer type and application rate, the soil alkali-hydrolyzable nitrogen content decreased with the increase in soil depth (Table S8). The soil alkali-hydrolyzable nitrogen content at 0–20 cm was from 24.2% to 32.3% higher than that at 20–40 cm at jointing stage in both years, and from 22.3% to 47.4% higher than that at 40–60 cm, respectively (Table S8).

The soil nitrate nitrogen content decreased with the increase in soil depth and increased with the increase in the fertilizer application rate (Figure 4a; Table S9). According to the average fertilizer type and application rate, the soil nitrate nitrogen content at 0−20 cm was 26−60.2% and 28.6–66.5% higher than that at 20−40 cm, and 34.9−80% and 37.4−80.5% higher than that of 40−60 cm at whole growing seasons in 2021 and 2022, respectively (Table S9). When using the average fertilizer application rate, the soil nitrate nitrogen content obtained with the chemical fertilizer was 12.2% and 29.7% higher than that obtained with the organic fertilizer at jointing stage in 2021 and 2022, respectively (Table S9). However, the average soil nitrate nitrogen content obtained with the chemical fertilizer was 16.8% and 9.9% lower than that obtained with the organic fertilizer at maturing stage in 2021 and 2022, respectively (Table S9). The soil ammonium nitrogen content increased with the increase in the nitrogen fertilizer application rate on average for all factors (Figure 4b). According to the average fertilizer type and application rate, the soil ammonium nitrogen content at 0−20 cm was 21% and 12.6% higher than that at 20−40 cm, and 30.9% and 19.5% higher than that at 40−60 cm at jointing stage in 2021 and 2022, respectively (Table S10). When using the average fertilizer application rate, the soil ammonium nitrogen content obtained with the chemical fertilizer was 14.4−25.8% and 1.9−19.5% higher than that obtained with the organic fertilizer at the jointing stage in 2021 and 2022, respectively (Table S10). However, the average soil ammonium nitrogen content obtained with the chemical fertilizer was 50.8−80.1% and 63.7−96.9% lower than that obtained with the organic fertilizer at the maturing stage in 2021 and 2022, respectively (Table S10).

The effects of different treatments on the soil available potassium content were not significant (Figure 4c). The soil available potassium content decreased with the increase in soil depth. According to the average fertilizer type and application rate, the soil available potassium content at 0–20 cm was 11.8–16.7% and 10.3–17.4% higher than that at 20–40 cm, and 11.1–19.8% and 5.2–17.7% higher than that at 40–60 cm throughout the whole growing seasons in 2021 and 2022, respectively (Table S11). According to the average fertilizer application rate and growth stage, the soil available potassium content obtained with the chemical fertilizer was 11.7% and 9% lower than that obtained with the organic fertilizer in 2021 and 2022, respectively (Table S11). When using the same nitrogen fertilizer application rate, the soil organic matter content of organic fertilizer was higher than that obtained with the chemical fertilizer (Figure 4d). According to the average fertilizer type and application rate, the soil organic matter content at 0–20 cm was 21.3% and 36.9% higher than that at 20–40 cm, and 28.7% and 35.3% higher than that at 40–60 cm at the jointing stage in 2021 and 2022, respectively (Table S12). When using the average fertilizer application rate, the soil organic matter content obtained with the chemical fertilizer was 6.6–14.7% and 3.9–14.6% lower than that obtained with the organic fertilizer throughout the whole growing seasons in 2021 and 2022, respectively (Table S12).

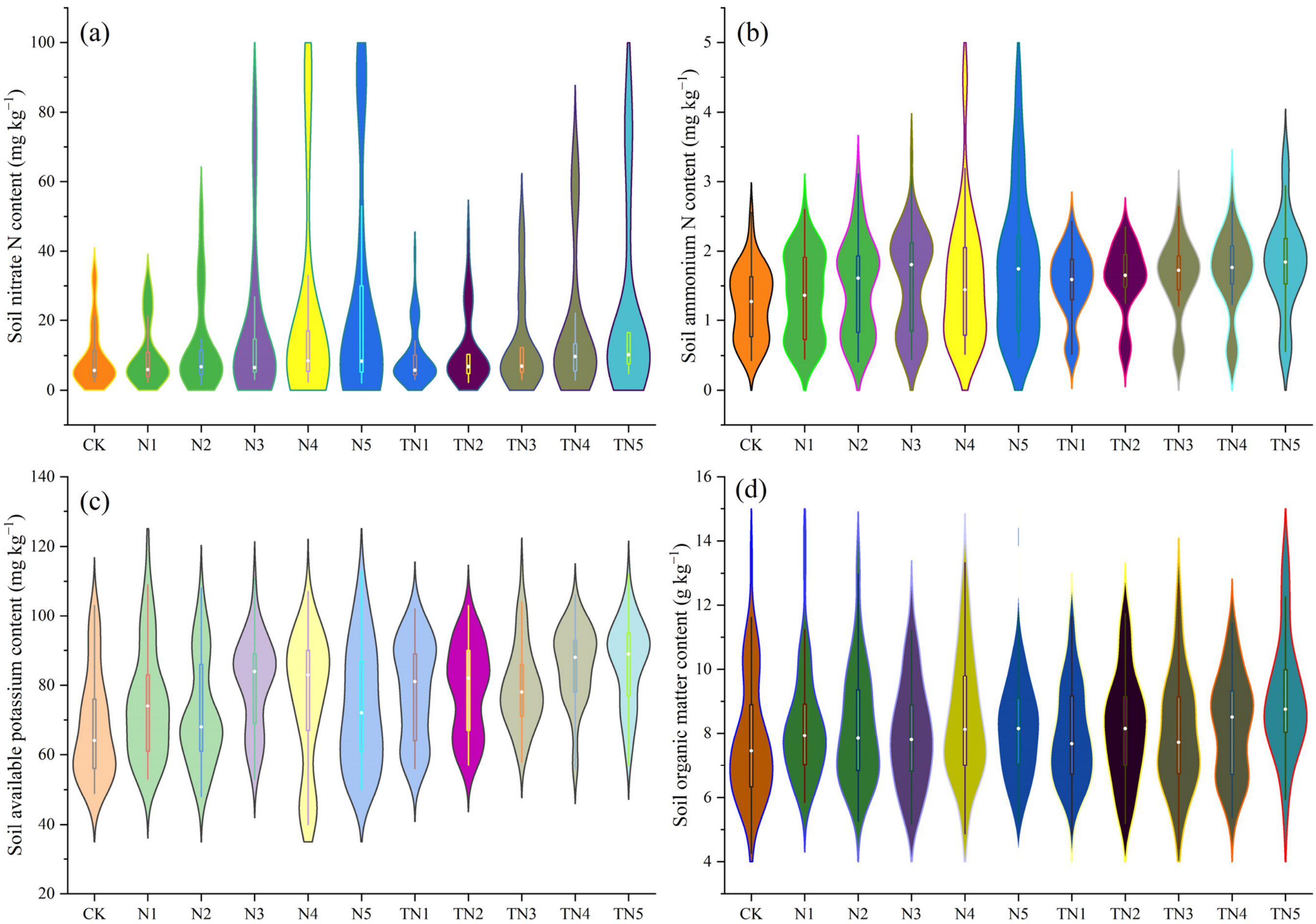

Figure 4. The mean soil nitrate nitrogen content (**a**), soil ammonium nitrogen content (**b**), soil available potassium content (**c**), and soil organic matter content (**d**) were affected by the different fertilizer types and application rates.

3.3. Soil Biological Indicators

Averaging across all factors, soil urease activity decreased, and soil catalase activity increased with the increase in the nitrogen fertilizer application rate (Figure 5a,b). According to the average year, fertilizer type, and fertilizer application rate, the soil urease activity at 0–20 cm was 24.5% and 33.9% higher than that at 20–40 cm and 40–60 cm in the jointing stage, respectively (Table S13). When using the average fertilizer application rate, the soil urease activity obtained with the chemical fertilizer was 2.8–17.7% and 10.8–26.6% lower than that obtained with the organic fertilizer at the jointing stage in 2021 and 2022, respectively (Table S13). Similar results were found in the jointing and maturing stages (Table S13). Averaging across all factors, the soil catalase activity decreased with the increase in the nitrogen fertilizer application rate (Figure 5a). At the jointing stage, the average soil catalase activity at 0–20 cm was 8.3% and 5.6% higher than that at 20–40 cm and 40–60 cm, respectively (Table S14). However, the soil catalase activity increased with the increase in soil depth at the maturity stage (Table S14). Throughout the whole growth stage, when using the average fertilizer application rate, the soil catalase activity obtained with the chemical fertilizer was 2.7–26.4% higher than that obtained with the organic fertilizer (Table S14).

Averaging across all factors, soil sucrase activity and soil phosphatase activity increased with the increase in the nitrogen fertilizer application rate (Figure 5c,d). According to the average fertilizer type and application rate, the soil sucrase activity at 0–20 cm was 21.4–48% and 20.9–40.2% higher than that at 20–40 cm, and 20.3–63.4% and 18.7–62.4% higher than that at 40–60 cm throughout the whole growing season in 2021 and 2022, respectively (Table S15). When using the average fertilizer application rate, the soil sucrase activity obtained with the chemical fertilizer was 1–50.9% and 8.9–48.5% lower than that obtained with the organic fertilizer in 2021 and 2022, respectively (Table S15). According to the average year, fertilizer type and application rate, the soil phosphatase activity at 0–20 cm was 37.7% and 52.8% higher than that at 20–40 cm and 40–60 cm at the jointing stage, respectively (Table S16). Similar results were found at the jointing and maturing stages (Table S16). When using the average fertilizer application rate, the soil phosphatase activity obtained with the chemical fertilizer was 2.3–21.9% lower than that obtained with the organic fertilizer in both years (Table S16).

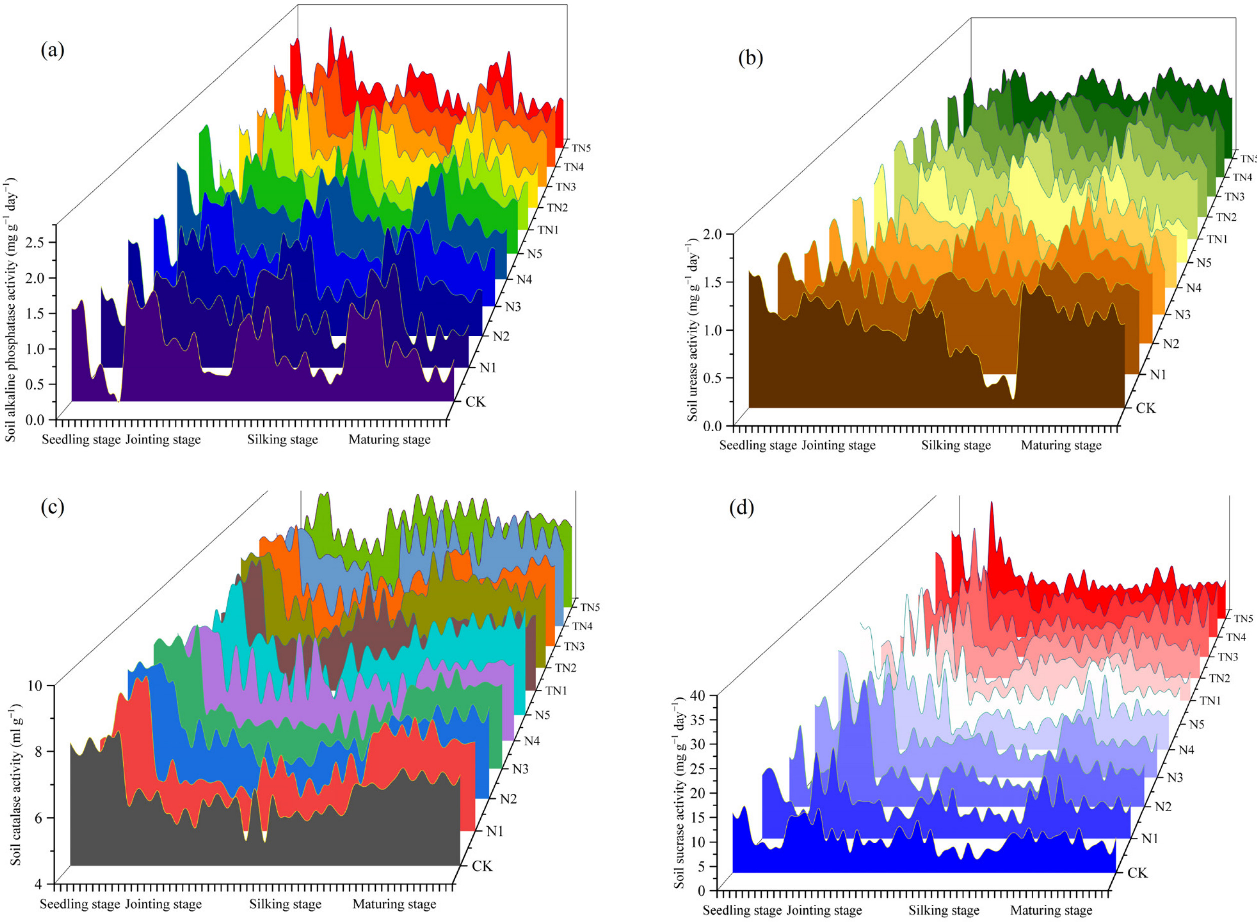

Figure 5. The mean soil urease activity (**a**), soil catalase activity (**b**), soil sucrase activity (**c**), and soil phosphatase activity (**d**) were affected by the different fertilizer types and application rates.

At 0–20 cm, the soil bacteria quantity obtained with the TN5 treatment was significantly higher than that obtained with the other treatments at the jointing stage (Table 1). The soil bacteria quantity obtained with the organic fertilizer treatment was higher than that obtained with the chemical fertilizer treatment under the same nitrogen application rate (Table 1). The soil bacteria quantity decreased with the increase in soil depth (Table 1). According to the average fertilizer type and application rate, the soil bacteria quantity at 0–20 cm was 74.1% and 71% higher than that at 20–40 cm, and 85.9% and 83.5% higher than that at 40–60 cm at the jointing stage in 2021 and 2022, respectively (Table 1). Similar results were found at the maturing stage (Table 2). When using the average fertilizer application rate, the soil bacteria quantity obtained with the chemical fertilizer was 64.5–242.9% lower than that obtained with the organic fertilizer at the maturing stage in both years (Table 2).

Table 1. The soil bacteria quantity (SBQ), soil fungi quantity (SFQ), and soil actinomyces quantity (SAQ) were affected by fertilizer type and fertilizer application rate at the silking stage in 2021 and 2022.

Item		SBQs (10^6 CFU g^{-1})			SFQs (10^3 CFU g^{-1})			SAQs (10^6 CAU g^{-1})		
		0–20 cm	**21–40 cm**	**41–60 cm**	**0–20 cm**	**21–40 cm**	**41–60 cm**	**0–20 cm**	**21–40 cm**	**41–60 cm**
2021	CK	1.66 + 0.59 d	0.64 + 0.22 b	0.38 + 0.38 ab	1.64 + 0.72 c	1.68 + 0.73 c	1.29 + 2.23 a	4.48 + 1.9 def	3.27 + 0.54 cd	1.52 + 0.23 bcd
	N1	1.41 + 0.59 d	0.9 + 0.44 ab	0.51 + 0.22 ab	3.31 + 1.9 c	1.69 + 0.74 c	0.81 + 0.7 a	8.65 + 1.04 b	6.11 + 0.58 a	4.36 + 1.02 a
	N2	3.2 + 0.8 cd	0.51 + 0.22 b	0.38 + 0.38 ab	6.12 + 2.45 c	2.04 + 0.71 c	1.63 + 0.7 a	5.8 + 0.82 bcd	3.58 + 0.29 bcd	1.95 + 0.6 b
	N3	2.05 + 0.59 d	1.02 + 0.22 ab	0.26 + 0.22 b	2.93 + 1.91 c	2.47 + 1.24 bc	1.65 + 1.89 a	11.76 + 1.71 a	3.27 + 0.42 cd	0.9 + 0.18 bcd
	N4	2.56 + 0.8 cd	1.41 + 0.59 ab	0.77 + 0.38 abc	3.8 + 1.26 c	2.98 + 0.74 bc	0.84 + 1.46 a	8.41 + 0.58 b	5.14 + 0.51 ab	0.55 + 0.18 cd
	N5	3.45 + 0.38 cd	1.02 + 0.44 ab	0.9 + 0.44 abc	2.98 + 1.47 c	1.71 + 0.74 c	1.69 + 0.74 a	7.63 + 0.76 bc	5.06 + 0.64 ab	1.25 + 0.44 bcd
	TN1	4.35 + 1.35 cd	1.66 + 0.59 ab	0.51 + 0.59 bc	8.77 + 1.83 bc	2.9 + 1.44 bc	2.07 + 2.59 a	6 + 0.59 bcd	4.13 + 0.53 bc	0.39 + 0.07 d
	TN2	6.14 + 2.03 c	2.05 + 0.59 ab	0.9 + 0.22 abc	8.14 + 1.48 bc	4.17 + 1.92 bc	2.92 + 1.92 a	4.25 + 0.24 def	2.53 + 0.58 cde	1.21 + 0.59 bcd
	TN3	10.49 + 1.93 b	2.43 + 0.22 ab	0.9 + 0.59 abc	6.67 + 3.16 c	8.76 + 3.82 b	3.98 + 0.68 a	2.65 + 0.7 ef	2.1 + 0.47 de	0.78 + 0.24 bcd
	TN4	11.13 + 2.3 b	2.05 + 0.97 ab	1.92 + 0.77 a	14.56 + 4.35 b	17.26 + 5.39 a	3.21 + 1.39 a	2.06 + 0.47 f	1.4 + 0.2 e	0.43 + 0.36 d
	TN5	18.17 + 1.55 a	3.07 + 1.92 a	1.66 + 0.59 ab	37.75 + 4.91 a	4.05 + 1.4 bc	1.7 + 0.74 a	5.26 + 1.24 cde	3.19 + 1.12 cd	1.87 + 0.47 bc
2022	CK	1.54 + 0.38 d	0.7 + 0.24 c	0.4 + 0.4 c	2.05 + 0.71 c	2.05 + 1.43 c	1.22 + 1.22 a	5.06 + 0.94 d	3.43 + 0.38 cde	1.44 + 0.27 bcd
	N1	1.79 + 0.44 d	0.98 + 0.49 bc	0.53 + 0.23 bc	2.9 + 1.9 c	1.71 + 0.74 c	1.66 + 0.72 a	8.45 + 0.85 b	6.04 + 0.44 a	4.17 + 0.7 a
	N2	1.66 + 0.22 d	0.56 + 0.24 c	0.4 + 0.4 c	6.25 + 3.32 c	3.23 + 1.39 c	2.5 + 1.26 a	5.92 + 0.66 cd	3.74 + 0.42 bcd	2.1 + 0.35 b
	N3	2.43 + 0.59 d	1.82 + 0.64 bc	0.27 + 0.23 c	5.71 + 2.55 c	1.63 + 0.71 c	1.26 + 1.26 a	11.37 + 1.25 a	3.31 + 0.44 cde	0.82 + 0.2 de
	N4	3.33 + 0.44 d	1.54 + 0.64 bc	0.8 + 0.4 abc	3.35 + 1.44 c	2.1 + 0.73 c	1.7 + 0.74 a	8.33 + 0.6 b	5.14 + 0.51 ab	0.51 + 0.18 de
	N5	3.45 + 0.38 d	1.26 + 0.42 bc	0.93 + 0.46 abc	2.55 + 1.27 c	2.11 + 0.74 c	1.28 + 1.29 a	7.71 + 0.65 bc	4.99 + 0.66 ab	1.09 + 0.18 cde
	TN1	4.48 + 1.35 cd	1.12 + 0.24 bc	0.4 + 0.4 c	3.38 + 1.46 c	2.98 + 0.74 c	1.69 + 0.74 a	6.11 + 0.64 cd	4.25 + 0.71 bc	0.35 + 0.12 e
	TN2	6.78 + 0.97 c	2.1 + 1.11 abc	0.93 + 0.23 abc	6.85 + 1.95 c	9.56 + 3.14 b	4.38 + 1.37 a	4.17 + 0.24 de	2.73 + 0.24 def	1.36 + 0.36 bcd
	TN3	10.24 + 1.6 b	3.93 + 1.35 a	0.93 + 0.61 abc	15.77 + 3.17 b	17.26 + 5.39 a	3.61 + 1.2 a	2.88 + 0.44 ef	2.18 + 0.36 ef	0.74 + 0.27 de
	TN4	11.52 + 1.76 b	2.66 + 0.24 ab	2.13 + 0.83 a	38.55 + 5.27 a	4.59 + 1.92 bc	2.04 + 0.7 a	1.95 + 0.29 f	1.44 + 0.13 f	0.55 + 0.24 de
	TN5	18.17 + 1.55 a	2.24 + 0.64 abc	1.87 + 0.61 ab	9.17 + 1.84 bc	2.48 + 1.25 c	2.05 + 1.43 a	4.87 + 0.59 de	3.51 + 0.65 cde	1.79 + 0.36 bc

Note: Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the HSD test. Each value is the mean ± SD (n = 3).

Table 2. The soil bacteria quantity (SBQ), soil fungi quantity (SFQ), and soil actinomyces quantity (SAQ) were affected by fertilizer type and fertilizer application rate at the maturing stage in 2021 and 2022.

		SBQm (10^6 CFU g^{-1})			**SFQm (10^3 CFU g^{-1})**			**SAQm (10^6 CFU g^{-1})**		
		0–20 cm	**21–40 cm**	**41–60 cm**	**0–20 cm**	**21–40 cm**	**41–60 cm**	**0–20 cm**	**21–40 cm**	**41–60 cm**
2021	CK	10.24 + 4.25 c	0.84 + 0.42 c	0.27 + 0.23 b	5.42 + 1.17 b	4.4 + 1.17 a	5.42 + 1.17 b	3.15 + 1.23 d	2.53 + 0.85 cde	2.02 + 0.58 c
	N1	17.02 + 7.89 bc	0.84 + 0.42 c	0.13 + 0.23 b	9.48 + 7.69 ab	5.08 + 4.06 a	9.48 + 7.69 ab	18.3 + 1.17 a	5.34 + 1.15 ab	0.86 + 0.18 a
	N2	16.51 + 1.02 bc	0.98 + 0.64 c	0.4 + 0.4 ab	9.14 + 4.06 ab	4.4 + 2.11 a	9.14 + 4.06 ab	10.24 + 0.58 bc	5.06 + 1.79 abc	1.67 + 0.89 c
	N3	13.05 + 1.54 c	0.98 + 0.49 c	0.53 + 0.23 ab	9.48 + 5.11 ab	4.74 + 0.59 a	9.48 + 5.11 ab	7.05 + 2.88 bcd	2.84 + 0.88 bcde	6.23 + 1.15 b
	N4	11.52 + 4.36 c	1.26 + 0.42 bc	0.93 + 0.23 ab	10.16 + 2.03 ab	5.08 + 3.05 a	10.16 + 2.03 ab	7.67 + 1.09 bcd	5.8 + 0.94 a	2.06 + 0.53 c
	N5	19.32 + 4.89 bc	0.98 + 0.24 c	0.53 + 0.23 ab	6.09 + 2.69 b	4.4 + 0.59 a	6.09 + 2.69 b	7.28 + 1.25 bcd	2.53 + 0.83 cde	2.49 + 1.23 c
	TN1	14.59 + 2.3 c	1.12 + 0.64 c	0.67 + 0.23 ab	9.14 + 2.03 ab	4.74 + 0.59 a	9.14 + 2.03 ab	10.63 + 1.35 b	3.47 + 0.64 abcde	1.95 + 0.47 c
	TN2	26.62 + 9.6 abc	1.68 + 1.52 bc	2 + 2.23 ab	11.85 + 3.85 ab	9.48 + 1.55 a	11.85 + 3.85 ab	5.06 + 1.64 cd	2.3 + 0.76 de	11.88 + 2.06 c
	TN3	23.29 + 4.8 bc	2.1 + 1.11 bc	2.27 + 1.15 ab	14.9 + 1.55 ab	7.45 + 3.26 a	14.9 + 1.55 ab	3.7 + 1.23 d	3.43 + 0.44 abcde	2.65 + 0.59 c
	TN4	47.47 + 7.35 a	4.91 + 0.64 a	3.07 + 0.83 a	22.68 + 11.55 a	5.08 + 1.02 a	22.68 + 11.55 a	7.05 + 3.07 bcd	4.87 + 0.99 abcd	3.51 + 1.42 bc
	TN5	36.85 + 16.46 ab	3.51 + 1.06 ab	2.13 + 1.51 ab	15.91 + 7.76 ab	8.13 + 1.76 a	15.91 + 7.76 ab	9.58 + 2.33 bc	1.83 + 0.29 e	1.09 + 0.18 c
2022	CK	11.26 + 2.72 d	0.7 + 0.49 c	0.27 + 0.23 b	6.09 + 2.69 c	4.06 + 1.02 b	0.34 + 0.59 d	3.47 + 0.85 e	2.3 + 0.44 ef	2.18 + 0.47 def
	N1	14.59 + 2.3 cd	0.84 + 0.42 c	0.4 + 0.4 b	10.16 + 2.69 bc	4.4 + 1.17 ab	6.09 + 1.76 cd	17.91 + 1.52 a	4.95 + 0.49 ab	0.82 + 0.2 a
	N2	13.44 + 1.02 cd	1.12 + 0.24 c	0.53 + 0.23 b	17.94 + 5.59 ab	6.43 + 1.55 ab	2.71 + 1.55 bc	10.13 + 0.49 b	4.24 + 0.38 abcd	2.1 + 0.31 de
	N3	10.36 + 2.4 d	1.12 + 0.49 c	0.8 + 0.4 b	4.74 + 1.17 c	6.09 + 2.69 ab	2.37 + 0.59 bcd	7.17 + 1.05 c	3.08 + 0.58 cdef	6.04 + 0.99 b
	N4	21.63 + 1.97 bc	0.84 + 0.42 c	0.53 + 0.23 b	6.09 + 2.03 c	4.74 + 1.55 ab	1.69 + 1.17 cd	7.56 + 0.89 bc	5.8 + 0.94 a	2.06 + 0.53 def
	N5	18.3 + 3.13 cd	0.98 + 0.49 c	0.53 + 0.23 b	7.79 + 1.17 bc	4.74 + 1.17 ab	2.03 + 1.02 bcd	7.17 + 1.06 c	2.84 + 0.38 def	2.96 + 0.68 cd
	TN1	27.64 + 5.19 b	0.98 + 0.24 c	0.27 + 0.23 b	13.54 + 3.85 bc	7.11 + 1.76 ab	2.71 + 1.55 bcd	9.43 + 0.83 bc	3.39 + 0.54 bcde	1.91 + 0.49 def
	TN2	19.83 + 4.1 bc	2.24 + 0.88 bc	1.87 + 0.46 a	10.16 + 4.06 bc	3.72 + 1.17 b	1.35 + 0.59 b	4.36 + 0.55 de	2.45 + 0.54 ef	9.7 + 0.54 f
	TN3	16.51 + 1.02 cd	4.91 + 0.64 a	2.8 + 0.4 a	10.16 + 2.03 bc	5.76 + 2.11 ab	5.42 + 1.17 bcd	4.25 + 0.6 e	3.39 + 0.51 bcde	2.45 + 0.31 def
	TN4	43.63 + 2.88 a	3.79 + 0.73 ab	2.8 + 0.4 a	26.41 + 8.31 a	9.14 + 2.03 a	11.17 + 2.69 a	6.86 + 0.64 cd	4.56 + 0.61 abc	4.09 + 0.42 c
	TN5	21.24 + 1.17 bc	2.24 + 1.06 bc	1.87 + 0.46 a	14.9 + 1.55 bc	3.72 + 1.17 b	2.37 + 1.55 bcd	7.83 + 0.73 bc	1.79 + 0.29 f	0.97 + 0.18 ef

Note: Columns with the same letter represent values that are not significantly different at the 0.05 level of probability according to the HSD test. Each value is the mean ± SD (n = 3).

The soil fungi quantity decreased with the increase in soil depth (Table 1). In 2021, the soil fungi quantity at 0–20 cm was 48.6% and 77.5% higher than that at 20–40 cm and 40–60 cm when using the average fertilizer type and application rate, respectively (Table 1). When using the average fertilizer application rate, the soil fungi quantity obtained with the chemical fertilizer was 64–296.5% lower than that obtained with the organic fertilizer at jointing stage in both years (Table 1). The soil fungi quantity obtained with the chemical fertilizer was 11.5–67.9% lower than that obtained with the organic fertilizer at maturing stage when using the average fertilizer application rate in both years (Table 2). The difference in soil fungi quantity between the different treatments decreased gradually with the increase in soil depth (Tables 1 and 2).

In both years, the soil actinomyces quantity at 0–20 cm was 39–77.7% higher than that at 20–40 cm and 40–60 cm when using the average fertilizer type and application rate, respectively (Table 1). The soil actinomyces quantity obtained with the chemical fertilizer was 52.2%, 42.3%, and 48% higher than that obtained with the organic fertilizer at the jointing stage when using the average fertilizer application rate at 0–20 cm, 20–40 cm, and 40–60 cm, respectively (Table 1). However, when using the average fertilizer application rate, the soil actinomyces quantity at 40–60 cm obtained with the chemical fertilizer was 58.2% and 36.8% lower than that obtained with the organic fertilizer at the maturing stage in 2021 and 2022, respectively (Table 2). The highest soil actinomyces quantity was obtained with the N5 treatment (Table 1).

3.4. Correlation and Principal Component Analysis

There were significant ($p < 0.05$) correlations between grain yield and the soil salt content, soil nitrate nitrogen content, soil alkali-hydrolyzed nitrogen, soil available potassium content, soil catalase activity, soil sucrase activity, and soil phosphatase activity in the bivariate correlation analyses, and the correlation coefficients ranged from 0.43 to 0.74 (Figures 6 and S3). The soil salt content was positively correlated with soil nitrate nitrogen content, soil ammonium nitrogen content, soil alkali-hydrolyzed nitrogen, and soil organic matter content (Figures 6 and S4). The soil nitrate nitrogen content was significantly correlated with the soil ammonium nitrogen content, soil alkali-hydrolyzed nitrogen, soil organic matter content, and soil actinomyces quantity, and the correlation coefficients ranged from 0.68 to 0.87 (Figures 6 and S5). Soil alkali-hydrolyzed nitrogen was positively correlated with the soil available potassium content, soil organic matter content, soil catalase activity, and soil phosphatase activity (Figures 6 and S6). There were significant ($p < 0.05$) correlations between the soil available potassium content and the soil organic matter content and soil phosphatase activity in the bivariate correlation analyses (Figures 6 and S7). Soil catalase activity was highly correlated with soil sucrase activity, soil phosphatase activity, soil bacteria quantity, and soil fungi quantity (Figures 6 and S8). Soil sucrase activity was significantly correlated with the soil phosphatase activity, soil bacteria quantity, and soil fungi quantity (Figures 6 and S9). In the bivariate correlation analysis, soil phosphatase activity was significantly correlated with soil alkali-hydrolyzed nitrogen, soil available potassium content, soil catalase activity, and soil sucrase activity (Figures 6 and S3, S6, S8 and S9). PC-1 and PC-2 described 38.7% and 27.6% of the data variance, respectively, accounting for 66.3% of data variance (Figure 7). The number of components advocated by principal component analysis is shown in Figure S10. The first digital component describes the highest eigenvalue and was approved as one of the best digital components to keep. The principal component analysis shows that the organic fertilizer was more beneficial to soil health than the chemical fertilizer.

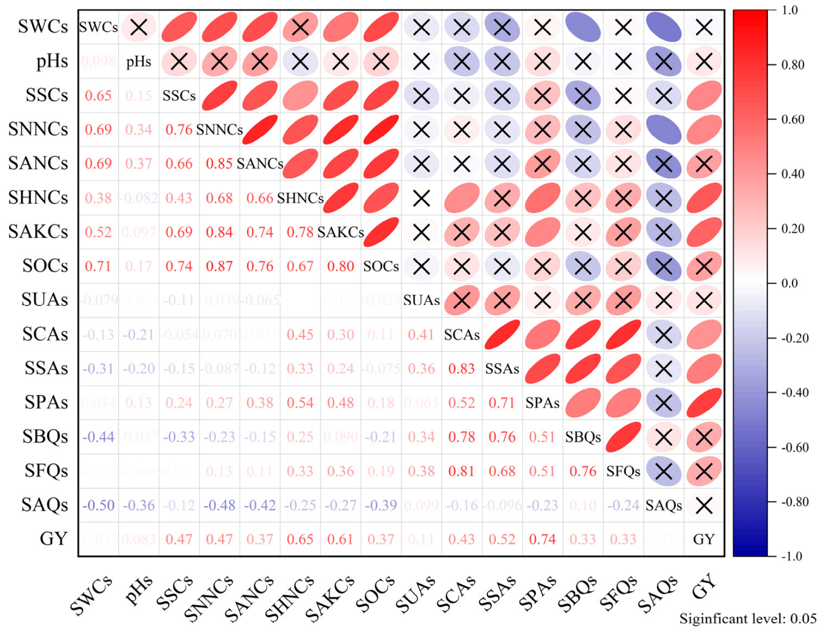

Figure 6. Correlations between grain yield and soil physical, chemical, and biological indicators in both years. Note: SWC, soil water content; pH, SSC, soil salt content; SNNC, soil nitrate nitrogen content; SANC, soil ammonium nitrogen content; SHNC, soil alkali-hydrolyzed nitrogen content; SAKC, soil available potassium content; SOC, soil organic matter content; SUA, soil urease activity; SCA, soil catalase activity; SSA, soil sucrase activity; SPA, soil phosphatase activity; SBQ, soil bacteria quantity; SFQ, soil fungi quantity; SAQ, soil actinomyces quantity; GY, grain yield.

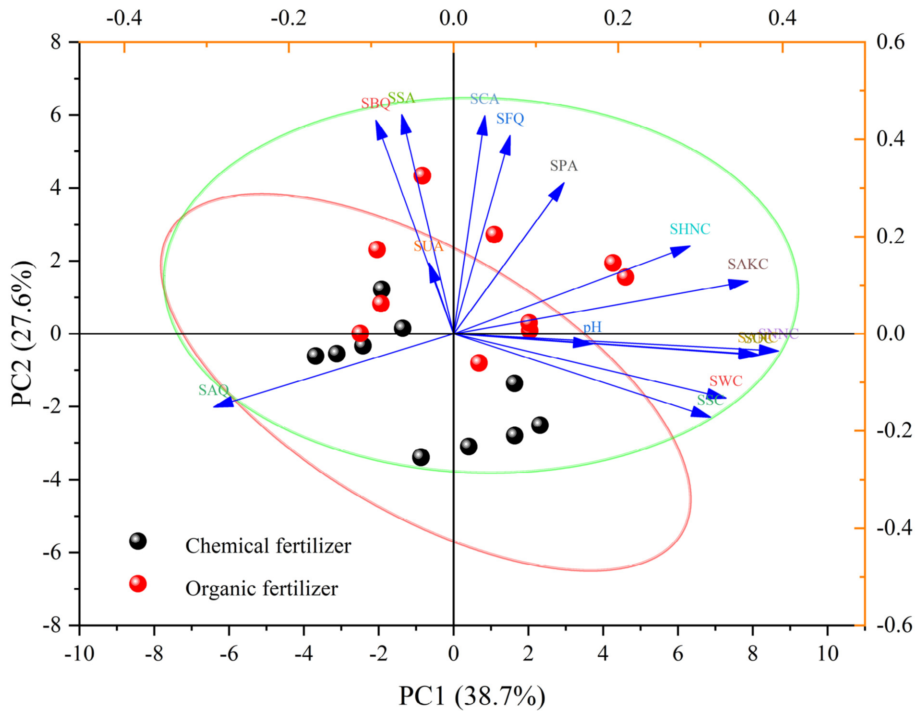

Figure 7. Principal component analysis of soil physical, chemical, and biological indicators in both years. Note: SWC, soil water content; pH, SSC, soil salt content; SNNC, soil nitrate nitrogen content; SANC, soil ammonium nitrogen content; SHNC, soil alkali-hydrolyzed nitrogen content; SAKC, soil available potassium content; SOC, soil organic matter content; SUA, soil urease activity; SCA, soil catalase activity; SSA, soil sucrase activity; SPA, soil phosphatase activity; SBQ, soil bacteria quantity; SFQ, soil fungi quantity; SAQ, soil actinomyces quantity.

4. Discussion

4.1. Factors Affecting Plant Growth and Grain Yield

In maize, the plant stature changes observed when treated with inorganic fertilizers exceeded those observed when treated with organic fertilizers at the jointing and filling stages, whereas at maturation, the reverse was noted. These findings suggest that organic fertilizers enhance the sustainability of maize growth, potentially attributable to their differential decomposition kinetics [22]. Organic fertilizers typically release inorganic nitrogen predominantly as ammonium ions after decomposition [23], with nitrates also being released, both readily assimilable by plants. Correspondingly, dry matter accumulation mirrored plant height trends, whereas stem diameter and leaf area demonstrated an inverse relationship. The latter may be due to the organic fertilizer facilitating soil microbial proliferation, altering microbial community compositions, and changing soil enzymatic activity [24].

Strategic nitrogen management is pivotal in agroecosystems for curtailing soil nitrate percolation, bolstering crop yields, and enhancing nitrogen use efficiency, which are critical for sustainable agricultural practices [25]. Excessive nitrogen application, coupled with substantial precipitation, can exacerbate nitrate nitrogen leaching into the subsoil during the summer maize season, increasing water contamination risks and reducing nitrogen utilization and maize productivity [26]. Empirical evidence indicates that grain outputs increase concomitantly with the increase in nitrogen application, with notable impacts on yield. The utilization of high-efficiency organic fertilizers can increase crop yields while preserving soil integrity, thus, supporting enduring food security and ecological safeguarding [27]. Additionally, supplementing inorganic with organic fertilizers can enhance soil conditions and yield [28]. The current investigation revealed negligible yield disparities between organic and inorganic fertilizer regimes. This may be attributed to organic modifications potentially reducing chemical fertilizer requirements, notwithstanding the brevity of the maize growth cycle and the protracted soil amelioration effects attributable to organic fertilizer application.

4.2. Factors Affecting Soil Physical and Chemical Properties

This investigation found that the mean soil moisture in the N5 treatment was marginally less than that the other treatments. The soil moisture profiles were notably influenced by variations in the fertilization levels, with higher fertilization levels leading to significant moisture depletion due to enhanced crop yields [29]. Research indicates that soil aggregate metrics such as the mean weight diameter, total porosity, and water retention are altered by organic fertilizer application [30]. However, the moisture levels in the soils treated with the organic fertilizers exhibited a greater stability than those treated with the inorganic fertilizers, with negligible differences between the two. This study also found that the soil moisture decreased with soil depth at the jointing stage, while at the silking and mature stages, the trend was reversed, possibly due to variable rainfall during these growth phases.

Regarding soil acidification through nitrogen fertilization, the primary mechanism involves hydrogen ion release during ammonium nitrogen nitrification and nitrate nitrogen leaching [31]. The organic fertilizer treatments yielded slightly higher pH values than the unfertilized controls. Continuous organic fertilizer application alters soil pH and organic matter, potentially increasing Cu concentrations in soil solution due to increased soil organic matter and aromatic compounds [32]. A study of the effects of organic fertilizer types and quantities on nitrogen mineralization in saline soils aimed to optimize soil nitrogen mineralization quality for sustainable use [33]. The results indicate a progressive decrease in soil salinity over the maize growth period, stabilizing later, likely due to maize's soil salt uptake reaching saturation [34]. Throughout maize growth, soil salinity was marginally higher with the chemical fertilizers than with the organic ones, possibly because organic fertilizers also significantly reduce saline soil's bulk density and salinity [35].

Inorganic nitrogen application was found to promote the mineralization of recalcitrant organic nitrogen, whereas organic fertilizers favored the mineralization of labile organic nitrogen [36]. Soil nitrate concentrations result from the interplay between plant uptake, soil microbiology, atmospheric nitrogen fixation, nitrogen mineralization, atmospheric deposition, denitrification, and volatilization [37]. Soil nitrate nitrogen, alkali-hydrolyzable nitrogen, and ammonium nitrogen levels increased with fertilizer use, but no significant difference was observed at the maize's mature stage, likely related to maize's nitrogen absorption and leaching dynamics. Seasonal variations were noted, with higher soil nitrate nitrogen in spring than in autumn [38]. In this study, it was observed that, at maize's jointing stage, the nitrate nitrogen in fertilized soil was 12.2% and 29.7% higher than in organically fertilized soil in the two years of 2021 and 2022, yet at maturity, fertilized soil nitrate nitrogen was 16.8% and 9.9% lower, respectively. This could be attributed to organic matter's soil structure improvement, water retention enhancement, and the promotion of biological transformations such as nitrogen mineralization [39]. Basal fertilizer resulted in a soil nitrate nitrogen content 1.65 times higher than that of the unfertilized control at a 0–10 cm depth 36 days post-sowing [40]. Organic fertilizers reduced nitrate nitrogen accumulation in the soil profile by 70% compared to mineral fertilizers alone [41].

Long-term NPK chemical and organic fertilizer use lowered soil exchangeable acid and aluminum levels, markedly increased available phosphorus and potassium contents, boosted soil carbon and nitrogen storage, and enhanced crop yields [41]. This study showed 11.7% and 9% reductions in soil available potassium with the use of fertilizers compared with the use of organic alternatives over two years. Organic fertilizer use increased soil available potassium at all maize growth stages, with effective potassium concentrations correlating positively with irrigation amounts during growth and flowering [42]. This aligns with findings demonstrating that organic fertilizers significantly improve the benefit average available phosphorus content in topsoil plants [43].

Soil organic matter quantity and quality serve as vital soil fertility indicators [44]. The soil organic matter content was higher with organic fertilizers than with chemical ones at equivalent nitrogen application rates. Although maize has the highest potential to decrease the soil organic matter content [45], long-term mineral nitrogen application (120 kg N ha^{-1} year^{-1}), while matching maize grain yield, results in a decrease in soil organic matter [46]. This study found a gradual reduction in soil organic matter content with increasing soil depth, possibly due to microorganisms at greater depths relying more on decadal soil organic matter for carbon than on recent plant-derived carbon [47].

4.3. Factors Affecting Soil Biological Indicators

Soil microorganisms are pivotal in plant growth and the sustainability of agricultural production [48]. Organic fertilizers increase soil bacterial and fungal numbers and diversity, whereas urea application markedly reduces them [49]. The increase in nitrogen fertilizer led to reduced soil urease and enhanced catalase activities. Hence, urease activity was notably lower in chemically fertilized soils than in organically fertilized ones. Throughout the growth cycle, urease activity in the soils treated with organic fertilizers surpassed that in the chemically treated soils. Research indicates that the soil surface application of organic fertilizers enriches the microbial substrate, thereby significantly altering microbial community composition and diversity [50]. Sole fertilizer reduction did not significantly impact soil catalase activity but did significantly decrease urease and acid phosphatase activities [51]. Further studies have confirmed that reducing chemical fertilizers and adding organic matter significantly enhances soil catalase and urease activities, though available soil phosphorus, potassium, and acid phosphatase activities experience a decline [52].

The increase in nitrogen fertilizer application correlates with reduced soil catalase activity. Organic fertilizers increase soil urease and catalase activities, yet chemical fertilizer application alone has no significant effect [51]. Soil urease, alkaline phosphatase, and catalase activities exhibit a significant positive relationship with soil nitrogen and grain yield. Catalase activity, crucial for plant growth, mitigates hydrogen peroxide's toxic effects via metabolic decomposition [53]. Soil carbon, nitrogen, and phosphorus cycling are integral to soil biochemical processes and reactions [54]. Soil catalase activity serves as an aerobiosis indicator, reflecting soil's redox potential [55]. This study linked high catalase activity to abundant aerobic bacteria and soil fertility. Fertilizer-induced activity inhibition may stem from the inability of single fertilizers to boost aerobic microorganism counts, possibly due to increased electrolyte concentrations under extreme salinization. The chemical fertilizer resulted in lower soil urease activity than the organic fertilizer at the jointing stage, and catalase activity waned as nitrogen application rate increased.

Organic fertilizer treatments surpassed chemical ones in soil bacterial and fungal counts at equivalent nitrogen levels. However, actinomycetes were 52.2%, 42.3%, and 48% more abundant in the chemically treated soils at the jointing stage across various soil depths. The organic fertilizers affected bacterial community distribution more significantly, while fungi were more responsive to the inorganic fertilizers [56]. Organic fertilization had a neutral effect on fungal biomass but tended to enhance bacterial biomass ratios via increased soil organic carbon [57]. This may be related to organic fertilizers promoting soil bacterial communities and root exudation, thus fostering plant growth. This study found that fertilizer type mainly influenced soil bacterial and fungal growth, with fungal numbers primarily affected by fertilizer quantity. Different fertilization strategies impact bacteria most significantly, and from a management perspective, fungal community structure precipitates a transitory surge in culturable bacterial populations [58]. Fertilizer varieties alter bacterial and fungal community distributions by affecting soil properties [59]. The soils treated with the organic fertilizers had bacterial counts 64.5–242.9% higher than those treated with chemical fertilizers, while actinomycetes counts were notably increased in the chemically fertilized soils compared to in the organically fertilized ones.

4.4. Correlation Analysis

This study found a correlation between maize grain yield and various soil parameters such as soil salinity; nitrate nitrogen levels; alkali-hydrolyzable nitrogen; available potassium; and enzymatic activities, including catalase, sucrase, and phosphatase. It was observed that maize yield and soil salinity were significantly correlated, likely due to increased rainfall during the crop's growth period, which may have leached salts away from the root zone. The close relationship between maize yield and soil nitrate nitrogen content could be attributed to a parabolic interdependency between soil nitrate levels and root length per plant, as well as between root length density and yield [60]. Notably, the nitrate nitrogen concentration in the root zone was inferior to other areas [40]. The use of organic fertilizers increased the available soil potassium content above that observed with the use of chemical fertilizers, enhancing both the growth and yield of maize. Positive correlations were found between crop growth, yield, and soil potassium levels, possibly because the organic fertilizer application increased photosynthetic efficacy and potassium translocation to grain [61].

Rhizosphere soil functions as an important buffer for microbial activities, primarily affecting soil bacteria and actinomycetes [62]. This study linked maize yield to soil enzyme activities, including catalase, sucrase, and phosphatase. In a previous study, under nitrogen scarcity, intercropped wheat–maize systems exhibited negative correlations with phosphorus uptake, catalase, acid phosphatase, and invertase activities. Soil enzymatic activities are crucial for soil quality and plant health [63]. Significant correlations were found between soil nitrate nitrogen and actinomycetes, and positive correlations were found between soil alkali-hydrolyzable nitrogen, available potassium, and phosphatase activity [64]. A principal component analysis favored organic fertilizers for soil health, likely due to enzyme activities facilitating nutrient availability and influencing the nitrogen fertilizer's chemical properties [65].

5. Conclusions

Throughout the entire growth stage, observations indicated that plant height, stem diameter, leaf surface area, and dry matter accumulation initially increased and subsequently decreased. Notably, the highest grain yield achieved with treatments N4 and TN4 surpassed that achieved with alternative modalities by a margin ranging from 4.5% to 45.7%. Regarding the volumetric water content of the soil, treatments that incorporated organic fertilizers demonstrated enhanced stability relative to treatments that incorporated inorganic fertilizers. A notable increase in soil pH was observed concomitantly with an increase in soil depth during the tillering stage, notwithstanding a lack of discernible distribution patterns across other growth stages. The salinity index of the soil exhibited a gradual decrease over the course of the maize vegetative season, eventually stabilizing. A comparative analysis during the tillering stage revealed that the mean concentration of nitrate nitrogen in the soil treated with the chemical fertilizers exceeded that in the soils treated with the organic fertilizers by 12.2% and 29.7%. Additionally, the content of soil organic matter obtained with the chemical fertilizer treatments was found to be inferior when compared with that obtained with the organic fertilizer treatments. An enzymatic analysis revealed a decrease in soil urease activity concomitantly with an increase in the nitrogenous fertilizer application rate. Microbiological enumeration indicated that the bacterial population density in the superficial 0–20 cm soil layer during the tillering stage increased by 74.1% and 71% in comparison to that in the 20–40 cm soil layer. Lastly, the fungal count in the soils subjected to the chemical fertilizers during the tillering stage decreased by a range of 64%–296.5% relative to that in the soils treated with the organic fertilizers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14050993/s1, Figure S1. Main meteorological data of maize during the two-year growing period. Figure S2. The relationship between maize grain yield and N fertilizer application rate in 2021 (a, chemical fertilizer and b, organic fertilizer) and 2022 (c, chemical fertilizer and d, organic fertilizer). Figure S3. The relationship between maize grain yield (GY) and soil salt content (SSC, a), soil nitrate nitrogen content (SNNC, b), soil alkali-hydrolyzed nitrogen (SANC, c), soil available potassium content (SAKC, d), soil catalase activity (SCA, e), soil sucrase activity (SSA, f), and soil phosphatase activity (SPA, g). Figure S4. The relationship between soil salt content (SSC) and soil nitrate nitrogen content (SNNC, a), soil ammonium nitrogen content (SANC, b), soil alkali-hydrolyzed nitrogen content (SHNC, c) and soil organic matter content (SOC, d). Figure S5. The relationship between soil nitrate nitrogen content (SNNC) and soil ammonium nitrogen content (SANC, a), soil alkali-hydrolyzed nitrogen content (SHNC, b), soil organic matter content (SOC, c) and soil actinomyces quantity (SAQ, d). Figure S6. The relationship between soil alkali-hydrolyzed nitrogen content (SHNC) and soil available potassium content (SAKC, a), soil organic matter content (SOC, b), soil catalase activity (SCA, c), and soil phosphatase activity (SPA, d). Figure S7. The relationship between and soil available potassium content (SAKC) and soil organic matter content (SOC, a) and soil phosphatase activity (SPA, b). Figure S8. The relationship between and soil catalase activity (SCA) and soil sucrase activity (SSA, a), soil phosphatase activity (SPA, b), soil bacteria quantity (SBQ, c), and soil fungi quantity (SFQ, d). Figure S9. The relationship between and soil sucrase activity (SSA) and soil phosphatase activity (SPA, a), soil bacteria quantity (SBQ, b) and soil fungi quantity (SFQ, c). Figure S10. The number of components advocated by principal component analysis. Table S1. The plant height was affected by fertilizer type and fertilizer application rate in 2021 and 2022. Table S2. The plant stem diameter was affected by fertilizer type and fertilizer application rate in 2021 and 2022. Table S3. The plant leaf area was affected by fertilizer type and fertilizer application rate in 2021 and 2022. Table S4. The plant dry matter accumulation was affected by fertilizer type and fertilizer application rate in 2021 and 2022. Table S5. The average soil water content in different growth stage (n = 3). Table S6. The average soil pH in different growth stage (n = 3). Table S7. The average soil salt content in different growth stage (n = 3). Table S8. The average soil alkali-hydrolyzale nitrogen content in different growth stage (n = 3). Table S9. The average soil nitrate nitrogen content in different growth stage (n = 3). Table S10. The average soil ammonium nitrogen content in different growth stage (n = 3). Table S11. The average soil available potassium content in different growth stage (n = 3). Table S12. The average soil organic matter content in different growth stage (n = 3). Table S13. The average soil urease activity in different growth stage (n = 3). Table S14. The average soil catalase activity in different growth stage (n = 3). Table S15. The average soil sucrase activity in different growth stage (n = 3). Table S16. The average soil phosphatase activity in different growth stage (n = 3).

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