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Coupled Effects of Straw Return Practices on Soil Microbial Function and Agricultural Productivity in Semi-Arid Region

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Abstract

Introduction This study investigates the effects of different straw return methods on soil properties, microbial activities, and maize yields in semi-arid regions. It compares three straw return practices: deep tillage with straw return (DPR), straw incorporated with subsoiling (SSR), and no-tillage mulching straw return (NTR). The goal is to assess the impact of these practices on soil health and agricultural productivity.

Methods A seven-year field experiment compared DPR, SSR, and NTR treatments on soil physical and chemical properties, microbial diversity, and maize yield. Parameters measured included soil bulk density, water content, alkaline nitrogen, available potassium, organic carbon, total nitrogen, microbial activity, and maize yield.

Results DPR significantly improved soil bulk density, water content, and levels of alkaline nitrogen, available potassium, organic carbon, and total nitrogen, enhancing soil fertility. NTR improved soil water content by reducing disturbance and favoring moisture retention. SSR increased microbial diversity and improved soil aeration. Path analysis showed that the utilization of carbohydrates by soil microorganisms positively affected maize yield by optimizing nutrient

and microbial carbon source utilization. DPR increased maize yield by 14.18%, and SSR increased it by 4.62%.

Discussion The results suggest that straw return practices optimize soil structure, improve fertility, and enhance microbial activity, promoting crop growth and productivity. Among the practices, DPR showed the most significant maize yield improvement. The study emphasizes the importance of microbial functions in nutrient utilization and demonstrates that straw incorporation supports sustainable agriculture in semi-arid regions.

Keywords: *Straw return,soil quality, maize yield, microbial activity, carbon source utilization*.

Introduction

The world's population is expected to reach approximately 9.8 billion by 2050; however, current arable land is unable to meet the growing demand for food (FAO.2018) In China, especially in regions such as Inner Mongolia and the Loess Plateau, the problem of soil degradation has been exacerbated by prolonged over-cultivation, excessive fertilizer use, and over-irrigation. In the Irrigation Area of Inner Mongolia's Tumu Chuan Plain, for example, long-term straw-off farming and shallow tillage have led to soil compaction, organic matter loss, and a decline in soil quality, which in turn has severely constrained agricultural productivity (Jayasudha *et al.*, 2024; L.-Q. Wang *et al.*, 2024).

As a strategy for agricultural resource management, straw return to the soil has gradually received widespread attention from researchers worldwide the world, and has been recognized as an important measure for improving soil quality and restoring soil ecological functions (P. Zhang *et al.*, 2025).By returning crop residues directly to the field, straw can be decomposed and transformed by soil microorganisms, promoting nutrient cycling to increase the organic carbon content of the soil, while simultaneously improving the physical structure of the soil. This, in turn, effectively increases crop yields and promotes soil health (B. Liu *et al.*, 2024; Song, Gao and Li, 2025; Wei *et al.*, 2025).A number of studies have demonstrated the importance of straw reclamation in improving soil health, crop yields and agricultural sustainability(Lal, 2004; Chang *et al.*, 2023). Therefore, exploring straw return methods suitable for the irrigation areas of the Tuomo River Plain will not only help restore soil health but also increase agricultural productivity and provide a sustainable solution for future food needs.

A number of studies have shown that returning straw to the soil can promote the increase of soil microbial numbers and species, improve the structure of microbial communities, enhance soil biological activity, and thus promote soil fertility and crop growth (Hao *et al.*, 2019). Deep turning of straw to return it to the soil increases the organic carbon content in the soil by accelerating the decomposition of straw and promotes the diversity and stability of the bacterial community (Li *et*

al., 2022; Zhang *et al.*, 2023, 2024). Deep plowing with straw return accelerates straw decomposition, increases organic carbon content in the soil, and promotes the diversity and stability of bacterial communities (Kalayu, 2019; Q. Liu *et al.*, 2024). However, different straw return methods, such as no-till straw covering, straw shredding with deep plowing, straw shredding with strip tillage, and high-residue retention, yield varying soil fertility improvement effects due to differences in climate and soil conditions across regions (Hu *et al.*, 2024). Furthermore, microorganisms in the soil grow and reproduce by metabolizing carbon sources, and different straw return methods have a significant impact on the metabolism patterns and efficiency of these carbon sources (Hu *et al.*, 2016; Pan *et al.*, 2023). For example, no-till straw covering reduces soil disturbance, helping to maintain soil structural stability, promote microbial carbon source metabolism efficiency, and positively contribute to soil fertility retention (Yin *et al.*, 2023). Although deep plowing and deep tillage with straw return accelerate straw decomposition and the release of organic carbon, excessive disturbance leads to the loss of some beneficial microorganisms, thereby affecting the stability of the soil microbial community (Zhou *et al.*, 2020).

Tumecheon Plain Irrigation District is located in the south-central part of Inner Mongolia, with a temperate arid and semi-arid climate, shallow soil tillage, low organic matter content, and water scarcity, which is one of the bottlenecks limiting the sustainable development of local agriculture. There is a lack of in-depth research on the combined effects of different straw return methods on soil microbial communities, enzyme activities, and microbial carbon source utilization in maize continuous cropping systems, as well as on the mechanisms by which these changes drive crop yield enhancement. In particular, the interrelationships between soil quality, microbial metabolic activities, and soil EMFs, and their mechanisms of action in soil health improvement and yield enhancement, remain insufficiently elucidated. To this end, this study assessed the combined effects of different straw return methods on soil physical properties, chemical properties, microbial activities, utilization of carbon sources by soil microorganisms, soil enzyme activities, and crop yields in a multi-year straw return positioning experimental field over four years of testing. It also explored the effects of straw return on soil microbial community, soil enzyme activity, and carbon utilization. The aim is to reveal the influence mechanism of different straw return methods on soil health, provide a scientific basis for the best practices of straw return under different soil conditions, and promote the optimization of straw return technology to enhance soil health, improve crop yield, and promote the sustainable development of agriculture.

2. Materials and Methods

2.1 Study Site

This study is based on the straw return test platform built by the group in the early stage (implemented in 2018), which is located in the China Cilechuan Modern Agricultural Expo Park (Beizhitu Village, Goumen Town, Tumet Right Banner, Baotou City, Inner Mongolia, latitude 40° 28′ 28″ N, longitude 110° 29′ 5″ E). The soil texture is sandy loam, and the area has a semi-arid mid-temperate continental monsoon climate, with an average annual temperature of 6 ℃ to 8 ℃, annual precipitation of 247.7, 280.4, 257.9, and 517.8 mm, a frost-free period of 140 days, an elevation of 1,015 m, an annual sunshine hour of 2,806 hours, and an annual active cumulative temperature of 3,000 ℃ to 3,500 ℃.Prior to the establishment of the straw return platform (i.e., in 2017), the soil fertility characteristics were as follows: organic matter content of 22.04 g/kg, alkali-hydrolyzable nitrogen content of 57.82 mg/kg, available phosphorus content of 3.57 mg/kg, and available potassium content of 84.97 mg/kg. Soil nutrient data are shown in Table S1, and the main meteorological data collected during the experiment are shown in Figure S1.

2.2 Experimental Design

The experimental platform began implementing various straw return practices in the fall of 2018, with four tillage methods: straw incorporated with deep tillage (DPR),straw incorporated with subsoiling (SSR), no-tillage mulching straw return (NTR), and farmers' shallow rotation (CK). The experiment started in the third year of straw return, from 2020 to 2024, and soil samples from the plow layer were collected on the experimental platform. The specific procedures are as follows: DPR:After maize harvest in autumn, straw is shredded using a rotary tiller, followed by deep plowing of the soil to a depth of 30-40 cm using a deep plow. The following spring, traditional sowing is performed with a conventional seeder. SSR : After maize harvest, straw is shredded using a rotary tiller, followed by deep tillage (35-40 cm) using a deep tiller. The straw is then mixed into the soil to a depth of 25 cm, and conventional sowing is performed the following spring. NTR : The shredded straw is spread over the soil surface after maize harvest, and sowing is done in the following spring using a no-till seeder. CK: Following local farming practices, the straw is removed after maize harvest, and shallow tillage (15 cm) is conducted. The conventional sowing method is used in the following spring.

Each treatment was replicated three times, resulting in 12 experimental plots, with each plot measuring 65 m × 6 m. Fertilizer was applied at rates of 3 kg ha^{-1} of pure nitrogen, 1.5 kg ha^{-1} of P_2O_5, and 1.5 kg ha^{-1} of K_2O. Nitrogen fertilizer was applied in a 3:7 ratio during the elongation and booting stages, while P_2O_5 and K_2O were applied as basal fertilizers. Other management practices followed those commonly used in the study area.

2.3 Soil and Crop Sampling

The sampling was conducted in May 2021 and May 2024, prior to maize sowing (the third and eighth consecutive years of the experiment), using the "S" sampling method. Soil samples were collected from the 0-45 cm soil layer of each plot using a soil auger (TG-25; Shaoxing Bowei Equipment Co., Ltd., China). The samples were passed through a 2 mm sieve to remove plant and animal residues, as well as other debris. The remaining soil was further sieved with a 2 mm sieve, and excess samples were discarded. The soil samples were then divided into four portions, sealed in bags, and immediately transported to the laboratory. One portion was stored at room temperature for the analysis of soil bulk density (BD), soil organic matter (SOM), total nitrogen (TN), alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), available potassium (AK), and organic matter (SOM). A second portion was stored at 4° C for the determination of soil hydrogen peroxide (H_2O_2) activity, RUBP carboxylase (RUBP) activity, soil β-glucosidase (S-β-GC) activity, and microbial carbon source utilization.

2.4 Determination of Indicators and Methods

2.4.1 Soil Properties Measurement

SM (Soil Moisture): Gravimetric method (Klute, A. 1986); BD : Aluminum can method (Blake, G. R., & Hartge, K. H. 1986); AN : Alkaline diffusion method (Bremner, 1965); AP : Olsen and Sommers method (‘Olsen SR, Sommers LE,1982); AK: Flame photometry method(Allen, S. E., & Grimshaw, H. M. 1986); SOM : Potassium dichromate method (Walkley and Black, 1934); TN : Kjeldahl method(Bremner, 1960); H_2O_2 : Potassium permanganate titration method (S. Zhang *et al.*, 2025); RUBP : Sandwich ELISA method (Díaz-González, 2005); S-β-GC : Near-infrared spectroscopy method (Dick *et al.*, 2013).

2.4.2 Calculation of Soil Quality Index

The soil quality index (SQI) was estimated using the total dataset method. First, all s oil properties were normalized to dimensionless scores ranging from 0 to 1. The soil prop erties were then divided into two categories. For properties that improve with soil quality (TN, AN, AP, AK, and SOM), the "more is better" method was applied using Equation 1. For properties where lower values indicate better soil quality (e.g., BD), the "less is bett er" method was applied with Equation 2 (Kalayu et al., 2019; Song *et al.*, 2024; Zhou et al. 2020)：

Ascending affiliation function: $S_L=\begin{cases} 0.1 & X \le X1 \\ 0.9 * （X - X1）/(X2 - X1) + 0.1 & X1 < X \\ 1.0 & X \ge X2 \end{cases}$ (1)

Descending affiliation function:$SL=\begin{cases} 0.1 & X \geq X2 \\ 0.9 * （X2 - X）/(X2 - X1) + 0.1 & X1 < X \\ 1.0 & X \geq X1 \end{cases}$ (2)

Next, principal component analysis (PCA) was used to determine the weight (Wi) of each indicator, based on the ratio of its variance to the cumulative variance. The soil quality was then calculated using the following equation:

$$\mathrm{SQI} = \sum_{i=1}^{n} Wi \times SL \quad (3)$$

Where Wi represents the weight of the i-th indicator, SL is the score of the indicator, and n is the total number of indicators.

The Biolog-ECO plate contains six categories of carbon sources (Table S2): carbohydrates (n = 10), amino acids (n = 6), polymers (n = 4), phenols (n = 2), amines (n = 2), and carboxylic acids (n = 7) (Preston-Mafham, Boddy and Randerson, 2002; Feigl *et al.*, 2017) 。

2.4.3 Soil EMF

Enzyme activity was used to evaluate the multifunctionality of the soil ecosystem (Delgado-Baquerizo *et al.*, 2020). Z-scores were applied to standardize the activity of each soil enzyme, followed by calculation of the mean value (Delgado-Baquerizo *et al.*, 2016):

$$\mathrm{Zi} = \frac{\mathrm{x-mi}}{\mathrm{sd}} \quad (4)$$

$$\mathrm{Zscore} = \mathrm{average(Zi)} \quad (5)$$

Where Zi represents the enzyme activity, x, mi, and sd correspond to the measured enzyme activity, the mean enzyme activity, and its standard deviation, respectively.

2.4.4 Carbon Source Utilization

Carbon source utilization capacity of soil microorganisms was estimated using average well coloration (AWCD) and determined using the Biolog-ECO microplate method (Zhou *et al.*, 2024). The procedure consisted of weighing a fresh soil sample equivalent to 5 g of dry soil in a sterile conical flask. Then, 45 ml of 0.85% sterile NaCl solution was added, sealed and shaken at 2, 000 r/min for 15 min, and left to stand for 15 min before collecting the supernatant. The supernatant was diluted 100-fold with sterile NaCl solution on a clean bench and inoculated into Biolog. eco microtiter plates with 8-channel spotter, 150-1 μl per well. inoculated plates were incubated in a biochemical incubator at 25 ℃ for 10 days, and good absorbance (OD) at 590 nm was read every 24 hours during the incubation period. Absorbance was measured according to the following

formula:

$$\text{Microbial metabolic activity: AWCD}=[\sum (Ci - R]/N \quad (6)$$

$$\text{Microbial diversity index: H}=-\sum \text{Piln（Pi）} \quad (7)$$

$$\text{Microbial uniformity index: E}=\text{H/ln(SR)} \quad (8)$$

$$\text{Microbial carbon source utilization rate: SAWCD}=(\sum \text{ODi/N})\frac{\sum ODi/n}{\sum ODi/N} \times 100\% \quad (9)$$

Where Ci is the OD value of each carbon source pore, R is the OD value of the control pore,N is the number of microporous holes (N=31), Pi is the ratio of the optical density ODi of the ith microporous hole to that of all the holes, SR is the number of carbon sources utilized, and SAWCD is the average rate of change of the color of each pore for a particular type of carbon source. n is the total number of microporous holes for a particular type of carbon source.

2.5 Yield Measurement and Seed Assessment

The measurement area of each plot was 36 square meters. Within each area, the number of ears harvested was counted and the fresh weight and moisture content of the grain after manual threshing were measured. The measurements were then converted to yield at 14% moisture content. In addition, 10 ears were left in each plot and air-dried. At 14% moisture content, the number of grains and 100-grain weight were measured.

2.6 Statistical Analysis

Line plots of microbial characteristics were drawn using Origin (2019).SPSS (SPSS 19.0, SPSS Inc., Chicago, USA) was used to perform analysis of variance (ANOVA), principal component analysis (PCA), Spearman's correlation analysis (P-value) and cluster analysis. The relationship between soil microbial characteristics and soil physicochemical properties was investigated using Spearman correlation analysis. One-way analysis of variance (ANOVA) was used to analyze whether the differences in soil physicochemical properties and microbial characteristics were significant (P < 0.05) under different organic substitution patterns. Differences between means were indicated by different letters using least significant difference (LSD; P < 0.05).

Partial Least Squares Path Modeling (PLS-PM) was used to determine the role of microbial carbon metabolism in improving soil fertility and crop yields under different straw returns using the “plspm” package of R software (Sanchez *et al*., 2013). The model was constructed based on theoretical relationships between variables, including exogenous (soil nutrients) and endogenous (microbial carbon utilization, microbial KEGG homologous genes, and microbial

composition).Path coefficients in the PLS-PM, which represent the effect of variables on each other, were normalized to a range from -1 to 1. Positive values indicate positive correlation and negative values indicate negative correlation. Bootstrap resampling (n=48) was performed to estimate the statistical significance of path coefficients and their confidence intervals. Absolute values of the path coefficients indicate the strength of the effect, and the associated p-values were used to assess the statistical significance of these relationships. Total effects were calculated to assess the overall impact of each variable on corn yield. The overall performance of the PLS-PM model was assessed using the goodness-of-fit (GoF) index.The GoF index was categorized into three levels: weak ($0.1 \leqslant GoF \leqslant 0.25$), moderate ($0.25 \leqslant GoF \geqslant 0.36$), and strong ($GoF > 0.36$).Models with a $GoF > 0.36$ were considered reasonable (Tenenhaus., 2004).

3. Results

3.1 Effect of Different Straw Return Methods on Soil Physical Properties

Tillage practices significantly affected soil bulk density (BD) and soil moisture content (SM) ($P < 0.01$; Fig S2). Compared with CK treatments, straw return treatments significantly decreased soil bulk density (1.68%-6.80%; $P < 0.05$) and increased moisture content (9.22%-12.61%; $P < 0.05$), whereas the DPR and SSR was significantly lower than NTR by 4.27% and 5.03%, respectively, while NTR treatment water content was not significantly different from DPR and SSR. Between years, the CK treatment increased the soil bulk weight yearly (2.09% in 2024 compared to 2021), while the DPR and SSR treatments significantly decreased the soil bulk weight (6.53% and 2.80% in 2024 compared to 2021, respectively, $P < 0.05$) and increased the soil water content (5.22 and 1.57 percentage points in 2024 compared to 2021, $P < 0.05$).The NTR treatment was the most prominent in increasing soil water content, by 5.40 percentage points in 2024 over 2021.

3.2 Effects of Different Straw Return Methods on Soil Chemical Properties

Soil alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), available potassium (AK), soil organic matter (SOM), and total nitrogen (TN) content of the treatments differed significantly among tillage practices, and between years.The straw return treatment significantly enhanced soil nutrients ($P < 0.01$; Fig S3a-3e), and the DPR treatment significantly enhanced the content of available potassium, organic carbon, and total nitrogen compared with SSR and DPR, whereas SSR significantly increased the alkali-hydrolyzable nitrogen, and NTR significantly increased the content of available phosphorus. Between different years, AN, AK, SOM and TN were significantly increased by 11.1%, 7.01%, 5.3% and 8.60% ($P < 0.05$), respectively, in DPR treatment in 2024 compared to 2021, while AK, SOM and TN were increased by 8.14%, 2.45%

and 8.27% respectivelyin SSR treatment, and AN, AP and TN were increased by 3.75%, 0.8 % and 6.7%, respectively, in NTR treatment.

3.3 Effects of Different Straw Return Methods on Soil Quality Index Over the Years

Soil quality index (SQI) as shown in Fig. There were highly significant differences ($P < 0.01$, Fig 1a-b) between tillage practices, years and interactions. The DPR treatments were significantly higher than the other treatments by 6.58%-206.90% ($P < 0.05$) among treatments; SSR and NTR were significantly higher than the CK treatments by 187.93% and 181.48% ($P < 0.05$), respectively. Across years, CK, DPR and SSR treatments SQI tended to increase with the year of implementation.

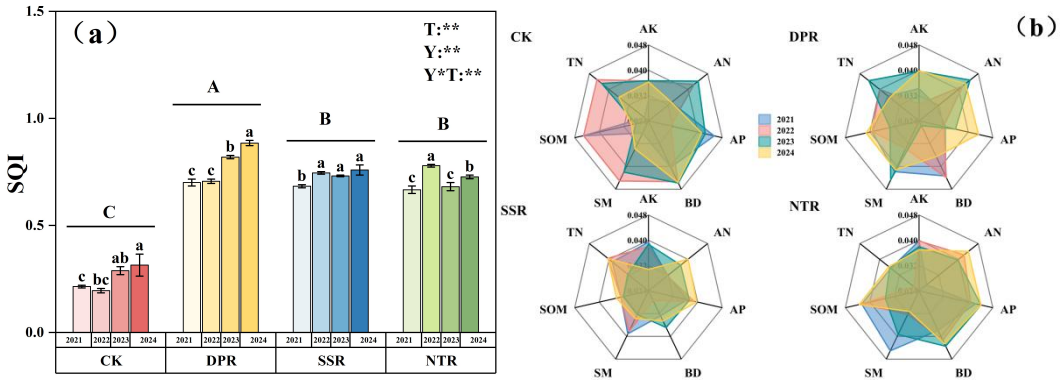


Figure 1. Soil Quality Index and Soil Physicochemical Properties Scores under Different Straw Return Methods. Error bars represent the standard error of the mean (n = 3). Different lowercase letters in the columns indicate significant differences between treatments ($P < 0.05$). CK, conventional shallow tillage; DPR, deep tillage with shredded straw return; SSR, deep loosening with mixed straw return; NTR, no-tillage with straw cover. SQI, Soil Quality Index. T, straw return treatment. Y, years. Significance levels: **, $P < 0.01$; *, $P < 0.05$; NS, no significant difference at $P > 0.05$.

3.4 Effects of Different Straw Return Methods on Soil Enzyme Activity Over the Years

Soil H_2O_2, S- β -GC, and RUBP enzyme activities of the treatments were significantly different among tillage methods, years, and their interactions ($P < 0.01$; Figure 2a-2c). Soil carbon cycle enzyme activities were significantly increased by straw return treatment compared with CK, and H_2O_2, S- β -GC, and RUBP activities were significantly increased by 11.10% - 14.55%, 13.18% - 23.72%, and 6.27% - 12.63% by DPR and SSR between return methods compared with NTR treatment, respectively. The enzyme activities of the straw return method treatments increased gradually with years, and the H_2O_2, S- β -GC, and RUBP enzyme activities increased by 92.35% - 108.49%, 48.12% - 98.27%, and 24.20% - 52.86%, respectively, in 2024 compared with 2021. Correlation analysis showed that H_2O_2, S- β -GC, and RUBP activities were closely related to soil organic matter, available potassium, nitrogen, and moisture ($P < 0.05$).

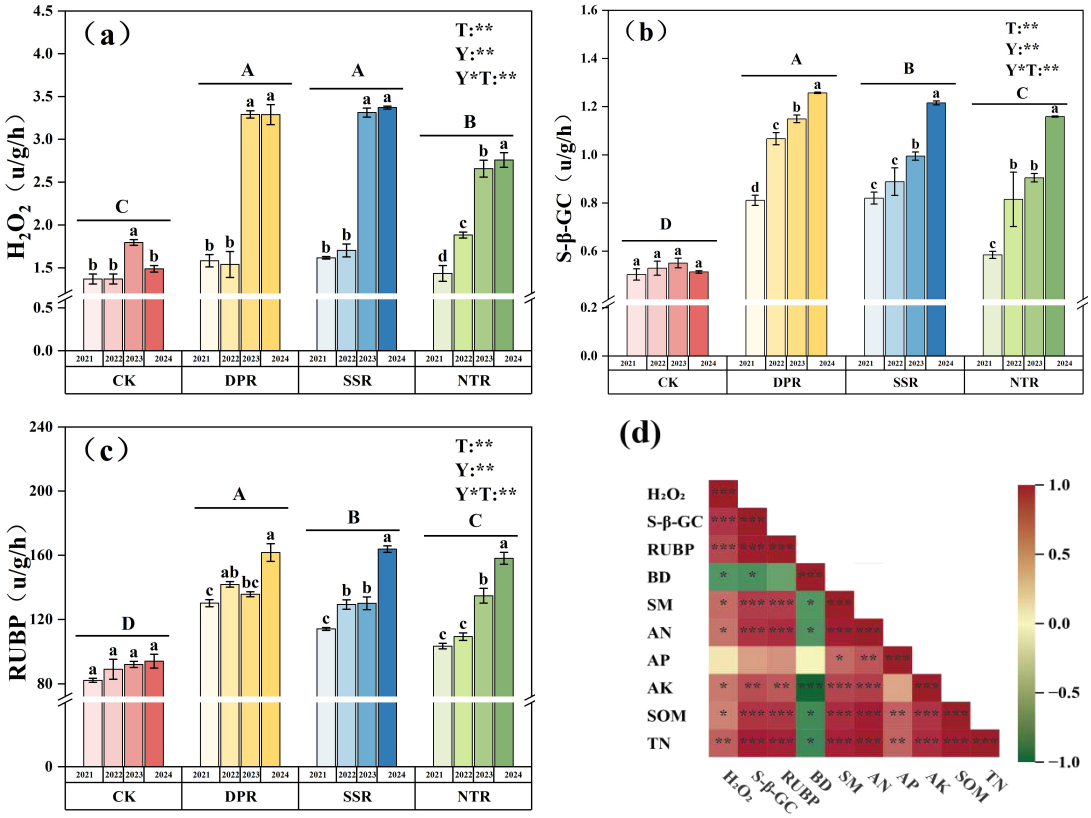


Figure 2. Comparison of Soil Enzyme Activities and Soil Properties under Different Straw Return Methods. H_2O_2, hydrogen peroxide enzyme; S-β-GC, soil β-glucosidase; RUBP, RUBP carboxylase.

3.5 Effects of Different Straw Return Methods on Soil Ecosystem Multifunctionality (EMF)

Soil EMF values characterize soil ecological functions, and there were highly significant differences among tillage practices, years, and their interactions ($P < 0.01$, Fig. 3a). The straw-returned treatment was significantly higher than CK among the treatments. Between the years of return, the EMF values increased significantly with year, and the DPR, SSR, and NTR treatments were significantly higher by 155.59%, 139.09%, and 105.48%, respectively, compared with the CK treatment ($P < 0.05$). Linear fitting analysis showed that soil EMF was positively correlated with soil quality index (SQI) ($R^2 = 0.63$, Fig. 3b).

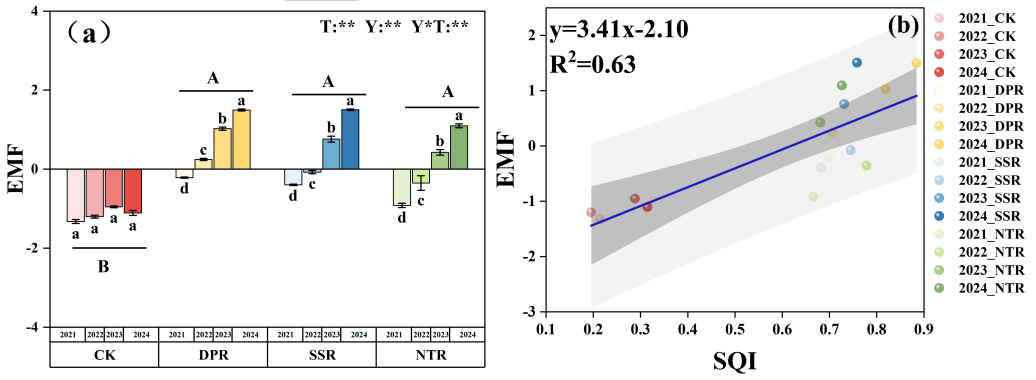


Figure 3. Soil Ecosystem Multifunctionality (EMF) under Different Straw Return Methods and Its

Relationship with Soil Quality Index (SQI).

3.5 Effects of Different Straw Return Methods on Soil Carbon Source Utilization Over the Years

The AWCD values of the straw return treatment increased with years, whereas the carbon utilization of the CK treatment decreased (Fig. S4). Soil microbial carbon metabolism activity (AWCD value) stabilized after 168 h of incubation, so the day 7 AWCD value ($AWCD_7$) was chosen as an indicator. Microbial diversity index and evenness index differed significantly ($P < 0.01$) between years. Overall, in the Evenness index, CK treatment was significantly higher than other treatments by 21.42% - 23.61%, and there was no significant difference among other treatments, while the diversity index was not significantly different among treatments. The Shannon index among different years showed a decreasing trend in CK treatment from 2021 to 2024, which was significantly lower by 46.85% compared to 2021, respectively. The Evenness index, which was significantly lower by 30.56%, 41.80%, and 37.70% in CK, DPR, and SSR treatments in 2024 compared to 2021, respectively.

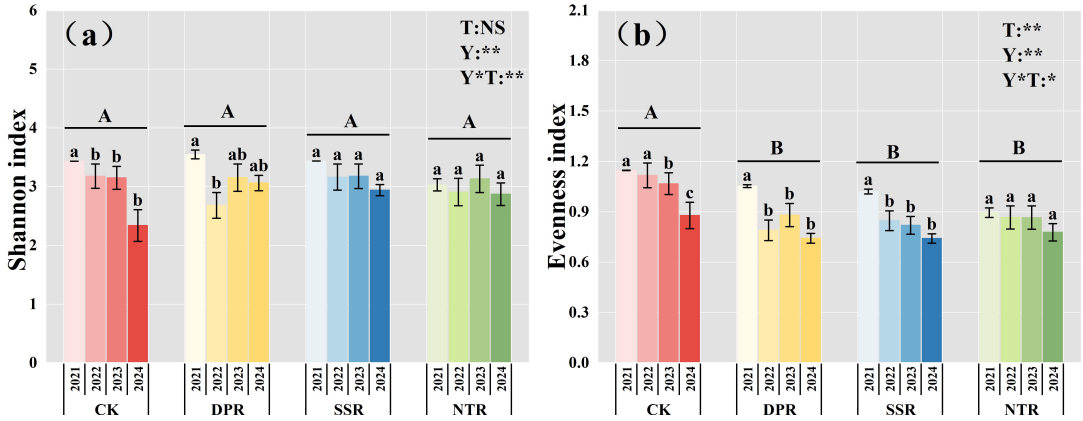


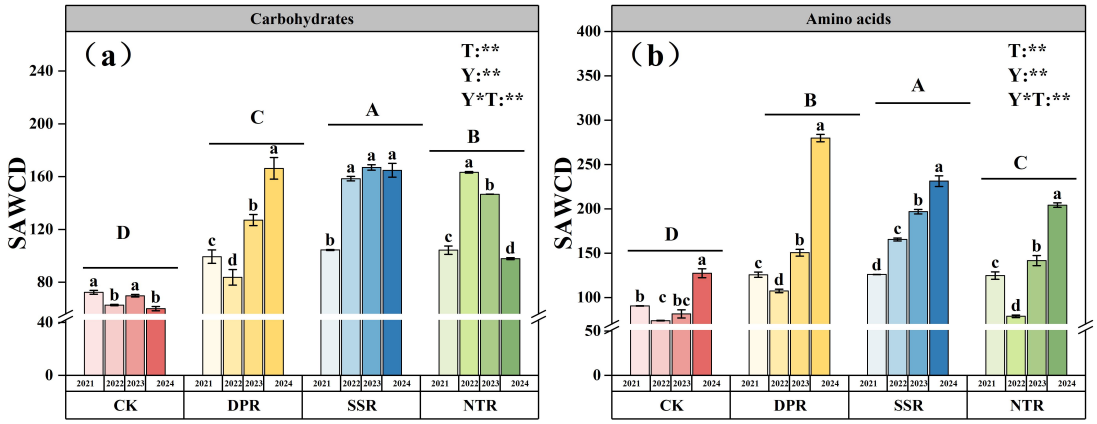
Figure 4. **Soil Microbial Community Diversity under Different Straw Return Methods.** Shannon index, diversity index; Evenness index, evenness index.

Based on the biological ecological panel, the utilization rates of the six major categories of carbon sources were analyzed and found to be significantly different among years, tillage, and their interactions ($P < 0.01$, Fig. 5a-f). Overall, among the treatments, the utilization of the six major categories of carbon sources was significantly higher in the straw-returned treatment than in CK, while DPR and SSR were significantly higher in the straw-returned treatment than in the NTR treatment, in which the utilization of carbohydrate-type, amino acid-type, carboxylic acid-type, and amine-type carbon sources in the SSR treatment was significantly higher than the other treatments ($P < 0.05$), with an average higher utilization of 55.18%, 44.05%, 71.13%, and 78.19%, with preference, while the DPR treatment had a preference for the utilization of polymer-based carbon sources, which was significantly higher than the other treatments by 14.01% - 146.14%.

Overall, among the treatments, the utilization rates of the six major categories of carbon sources were significantly higher in the straw-returned treatments than in CK, while DPR and SSR were significantly higher than in the NTR treatments. In this context, the utilization rates of carbohydrates, amino acids, carboxylic acids, and amines in the SSR treatment were significantly higher than in the other treatments ($P < 0.05$), with an average of 55.18%, 44.05%, 71.13%, and 78.19%, respectively, showing a preference for these six categories. Meanwhile, the DPR treatment had a utilization preference for polymer-based carbon sources, which was significantly higher ($P < 0.05$) than other treatments by 14.01% - 146.14%.

Between years, the utilization of various types of carbon sources in straw-returned treatments showed an increasing trend, specifically, the DPR treatment showed an increasing trend of preference for the utilization of sugars, amino acids, carboxylic acids, and amines; the SSR treatment showed an increasing preference for the utilization of sugars, amino acids, carboxylic acids, and amines year by year; the NTR treatment showed an increasing trend of preference for the utilization of amino acids, carboxylic acids, phenolic acids, and polymers, while the preference for sugars. The preference of soil microorganisms for carboxylic acids, amines, phenolic acids, and polymers under CK treatment showed a decreasing trend.

Correlation analysis showed that six types of carbon sources were positively correlated with soil carbon cycle-related enzymes ($P < 0.01$; Fig. 5g); carbohydrate carbon sources were positively correlated with soil TN, SOM, AK, AN, SM, and the Shannon index ($P < 0.05$). Amino acid carbon sources showed a highly significant positive correlation ($P < 0.01$) with soil TN, AN, and SM. Carboxylic acids, phenolic acids, and polymers showed highly significant positive correlations ($P < 0.01$) with soil TN, SOM, AN, and SOM.



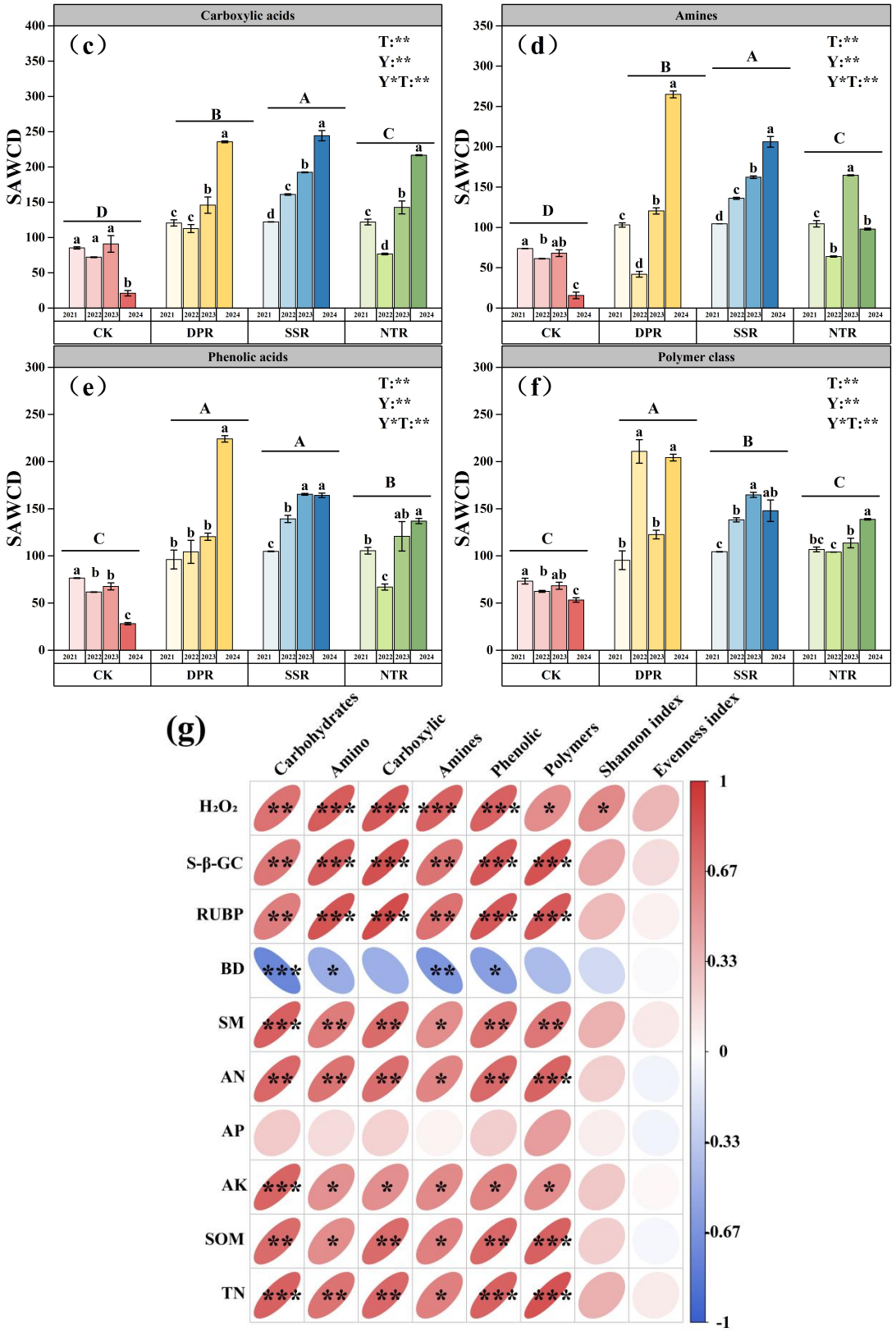


Figure 5. Carbon source utilization rates by soil microbes under different straw-return treatments.

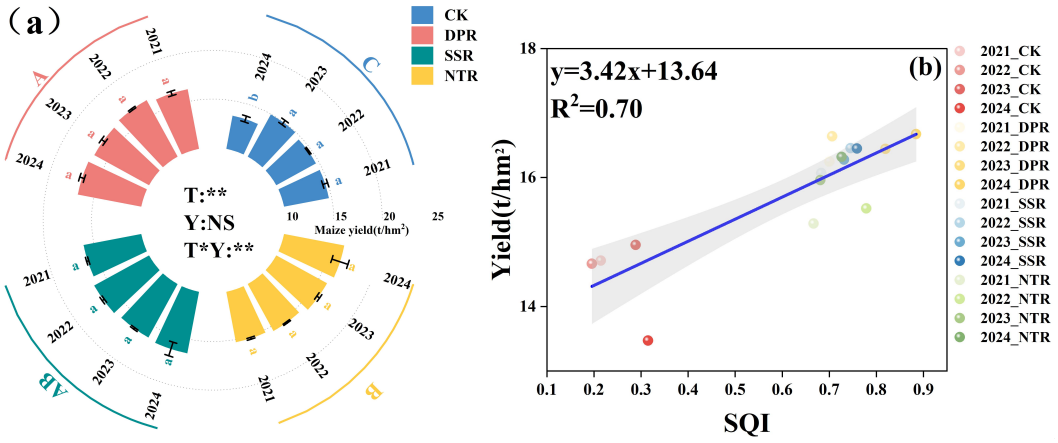
3.6 Corn Yield and Driving Factors under Different Straw Return Treatments

The straw return treatment (T), year (Y), and their interaction (T*Y) had a significant effect on corn yield ($P < 0.01$, Fig. 6a). The DPR treatment significantly increased corn yield by 14.18%

and 4.62% compared to CK and NTR, respectively, with no significant difference observed between DPR and SSR ($P > 0.05$). Linear regression analysis indicated a positive correlation between crop yield and the Soil Quality Index (SQI) ($R^2 = 0.7$), suggesting that improvements in soil quality contributed to increased corn yield (Fig. 6b).

The Partial Least Squares Path Modeling (PLS-PM) model, based on soil microbial activity, enzyme activity, and nutrient characteristics (Fig. 6c), revealed the path structure of "microbial metabolic function — enzyme activity — soil nutrients — yield." Soil carbon source metabolism (SAWCD1) acted as an exogenous latent variable, directly influencing SAWCD2, which further enhanced SAWCD3, significantly boosting the microbial community's functional activity. SAWCD2 promoted SAWCD3 activity, strengthening the microbial community’s regulation of soil enzyme activity. SAWCD3 optimized soil nutrient supply by regulating H_2O_2 levels, which in turn enhanced nutrient utilization via increased S- β -GC activity. Nitrogen (N) and potassium (AK) were strongly correlated, with AK enhancing soil potassium utilization. AK also facilitated the accumulation of Soil Organic Matter (SOM), thus improving soil quality. Ultimately, SOM significantly enhanced soil quality and increased corn yield, highlighting the critical role of soil organic matter accumulation in improving agricultural yield.Figure 6d displays the total effects of each latent variable on yield: Carboxylic acids (0.53), Amino acids (0.47), RUBP (0.30), AK (0.56), and Carbohydrates (0.46). Carbohydrates played a key role in influencing yield through multiple intermediary pathways.

The PLS-PM model demonstrated a good fit (GOF = 0.84) with a high explanatory power (R^2 for Yield = 0.85). These results indicate that there exists a multi-level interrelationship between soil microbial metabolic function, soil enzyme activity, and soil nutrients, with straw return treatments enhancing yield through the regulation of this system structure.



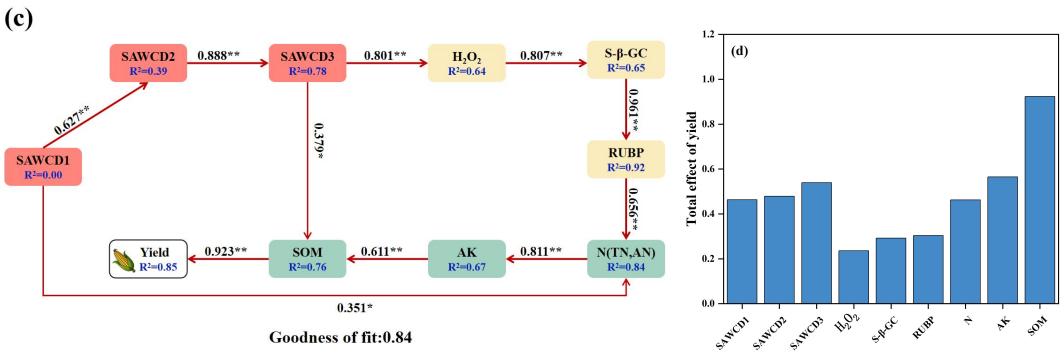


Figure 6. Relationship between Corn Yield and Soil Quality Index under Different Straw Return Treatments and Its Driving Factors.The study employed Partial Least Squares Path Modeling (PLS-PM) to investigate the impact of soil microbial activity, soil enzyme activity, and soil nutrients on corn yield under different straw return treatments. SAWCD1,Carbohydrates;SAWCD2,Amino acids,;and SAWCD3,Carboxylic acids. Red lines represent positive paths, while blue lines represent negative paths. The width of the lines indicates the size of the effect. The numbers on the lines represent the effect size, and statistical significance is marked with * and ** when the effect is significant at $p < 0.05$ and $p < 0.01$, respectively. Dashed lines represent non-significant pathways.

4. Discussion

4.1 The Impact of Different Straw Return Treatments on Soil Quality

The results of the present study showed that compared with CK, straw fertilization significantly improved the soil quality index (SQI) in all starw-return treatments and different years, with a maximum increase of 206.90% ($P < 0.05$), indicating that straw fertilization can significantly enhance the ecological function of the soil and improve the overall health of the soil system. This increase was mainly attributed to the improvement of soil organic matter content, physicochemical structure and microbial habitat conditions by straw fertilization (Anning *et al.*, 2023; R.-Z. Liu *et al.*, 2024). Among the three straw return methods, DPR has the most significant effect in improving SQI, and its advantages are mainly reflected in alleviating soil compaction, increasing porosity, and promoting the uniform distribution of straw and nutrients in the profile, thus accelerating soil structure remodeling and nutrient regeneration (Li *et al.*, 2024).In contrast, the SSR and NTR treatments promoted microbial diversity and water retention more significantly, with SSR improving aeration by breaking up the plow subsoil and increasing Shannon's diversity index by 32.98%, and NTR slowing down water evaporation and increasing soil water-holding capacity by reducing disturbance and maintaining ground cover (X. Wang *et al.*, 2024).The above differences indicated that there was a functional differentiation in the mechanism of soil quality improvement among the different methods: DPR was dominated by the structure-nutrient pathway, while SSR and NTR favored the micro-ecological regulation pathway (Liu *et al.*, 2023).In addition, the SQIs of CK, DPR and SSR treatments showed a continuous increasing trend with the prolongation of cropping years, indicating that straw return measures have significant cumulative effects and time-dependence, and the long-term application can help to realize the stable

enhancement of soil system functions (Zhu *et al.*, 2024).

4.2 The Impact of Different Straw Return Treatments on Soil EMF

Straw return significantly increased soil EMF, with all straw return treatments showing significantly higher EMF compared to the CK treatment (Fig. 3a). This suggests that straw input can enhance soil multifunctionality by increasing carbon source supply and activating microbial metabolic functions (Brown and Jones, 2024). There were notable differences in the extent of EMF enhancement among the different return methods, with SSR performing the best, followed by NTR and DPR treatments. SSR improved soil aeration and pore structure by breaking the plow pan, providing a more suitable habitat for microbial communities and promoting functional expression (Yao *et al.*, 2023). NTR, by maintaining surface cover and reducing human disturbance, created a stable and moist microenvironment, which was beneficial for microbial network formation in the long term (Xiao *et al.*, 2022; Wen *et al.*, 2023). Although DPR initially improved aeration and nutrient supply, its stronger disturbance may interfere with the surface microbial structure, limiting the sustained growth of EMF (Delgado-Baquerizo *et al.*, 2016). Moreover, EMF was significantly positively correlated with the Soil Quality Index (SQI) (R^2 = 0.63, Fig. 3b), indicating that improvements in physical and chemical properties provide the foundational support for microbial functional diversity expression (Huo *et al.*, 2024).

4.3 The Impact of Different Straw Return Treatments on Soil Carbon Source Utilization

The AWCD value reflects the efficiency of microbial carbon source utilization and carbon metabolic activity. The higher the AWCD, the stronger the microbial carbon source utilization and carbon metabolism activity (Bertini *et al.*, 2021). The results of this study show that different straw return treatments significantly altered the efficiency and preference of soil microbes for six types of carbon sources (carbohydrates, amino acids, carboxylic acids, amines, phenolic acids, and polymers) by regulating soil structure and nutrient conditions ($P < 0.01$). Compared to CK, all straw return treatments significantly enhanced carbon source metabolic activity, with the largest increases observed in DPR and SSR treatments. This indicates that organic matter input effectively enhances the metabolic potential and substrate adaptability of soil microbes (Liu *et al*.,2025). SSR treatment significantly increased the utilization of carbohydrates, amino acids, carboxylic acids, and amines, with respective increases of 55.18%, 44.05%, 71.13%, and 78.19% compared to other treatments. This suggests that SSR treatment improves soil aeration and the micro-ecological environment, promoting microbial community diversity and functional redundancy (Liu *et al.*, 2022). In contrast, DPR treatment exhibited a specific preference for polymer carbon sources, with

utilization rates 14.01% to 146.14% higher than those of other treatments. This is closely related to its ability to rapidly release macromolecular organic matter (Peng *et al.*, 2024).

Regarding temporal changes, the utilization rates of various carbon sources under straw return treatments generally showed an increasing trend over the years, reflecting a significant cumulative response (Ding *et al.*, 2024). Both SSR and DPR treatments continuously enhanced the utilization of soluble carbon sources, while NTR treatment progressively improved the utilization of amines, phenolic acids, and polymers, although the utilization of sugars began to decline slightly after 2022. Under the CK treatment, carbon source metabolic activity continuously declined, reflecting the coexistence of reduced microbial function and soil quality degradation.

Correlation analysis revealed significant positive correlations between carbon source utilization rates and the activities of carbon cycling-related enzymes (Fig.5g. $P < 0.01$), validating the enzymatic regulatory mechanisms of microbial metabolic activity (Delgado-Baquerizo *et al.*, 2016). Among these, the utilization rates of carbohydrates, amino acids, and carboxylic acids were significantly positively correlated with TN , SOM, AN, AK, SM, and Shannon index. These results suggest that microbial carbon source metabolism is not only influenced by the type of carbon source but is also jointly regulated by nutrient conditions and community structure (Liu *et al.*, 2023).

4.4 The Impact of Different Straw Return Treatments on Corn Yield and Its Driving Factors

The primary goal of straw return is to improve soil quality and achieve higher crop yields within a short period (Shrivastava and Kumar, 2015). This study indicates that straw return treatments (such as DPR, SSR, and NTR) significantly influenced corn yield ($P < 0.01$, Fig. 6a). The DPR treatment increased the yield by 14.18% and 4.62% compared to CK and NTR, respectively, while no significant difference was observed between SSR and DPR ($P > 0.05$), suggesting that DPR has a significant advantage in enhancing corn yield in the short term. This finding is consistent with research showing that straw return improves soil organic matter (SOM) and enhances nutrient utilization efficiency (Yan *et al.*, 2022). SOM directly promotes crop nutrient absorption and metabolic product synthesis by increasing soil available potassium (AK) and nitrogen (N) content (Wei *et al.*, 2023). The Soil Quality Index (SQI) was significantly positively correlated with corn yield ($R^2 = 0.7$, Fig. 6b), further confirming the role of soil quality improvement in boosting crop yield (Vizioli *et al.*, 2021).

The PLS-PM model revealed that SAWCD1 not only directly affects nutrient content but also optimizes soil fertility by regulating microbial carbon source utilization and enzyme activity (Fig. 6c). The effects of SAWCD1 significantly influenced corn yield through multiple intermediary pathways, particularly by enhancing soil enzyme activity and carbon source utilization efficiency

(Tian *et al.*, 2025). Moreover, the positive correlation between soil enzyme activity and crop yield indicates that straw return not only improves soil fertility through increased SOM and microbial activity but also promotes nutrient cycling by enhancing soil carbon metabolism (Bei *et al.*, 2022).

In conclusion, straw return enhances corn yield by improving microbial carbon metabolism, soil enzyme activity, and soil quality. Different straw return methods regulate microbial functions and soil nutrients through multiple pathways, providing a theoretical basis for agricultural yield enhancement and sustainable management.

5. Conclusion

Overall, this study demonstrated the effects of different straw-returning methods on soil quality, microbial function, and crop yield. Straw return significantly improved the soil quality index (SQI) and enhanced soil fertility by increasing soil organic matter, improving soil structure, and water retention capacity. DPR and SSR treatments significantly increased soil enzyme activities, promoted soil nutrient mineralization, and enhanced nutrient availability. NTR treatment significantly improved microbial diversity and carbon source utilization by reducing soil disturbance and maintaining surface cover, especially excelling in amino acid, carboxylic acid, and polymer carbon source utilization. Utilization efficiency, especially in the utilization of amino acid, carboxylic acid, and polymer carbon sources, was further promoted by improving microbial metabolism. Ultimately, straw return significantly increased corn yield, especially the DPR treatment, which increased the yield by 14.18%. This study provides a scientific basis for optimizing straw-returning technology, enhancing soil health and crop yield, and promoting sustainable agricultural development.

Author contributions

Performed the experiments:R.Z.L.,X.Y.Z.,X.Z.,S.P.H.,P.-R.L.,and X.F.Y. ,Analyzed the data: R.Z.L.Critically revised the manuscript for important intellectual content: J.L.G. and E.R. Wrote the paper: R.Z.L. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supporting information

At the very beginning of the experiment, we obtained the basic data on soil fertility status in 2020, as well as the data on physical and chemical properties of soil under different methods of straw returning, the average color of water absorption and color development (AWCD) data of soil microbial carbon source utilization profiles, and Biolog-ECO plate data during the period from 2021 to 2024.

Data availability

Data will be made available on request.

References

‘Allen, S. E., & Grimshaw, H. M. (1986). Methods in Soil Analysis Part 2. Chemical and Microbiological

Properties. American Society of Agronomy, Inc..pdf' (no date).

Anning, D.K. *et al.* (2023) 'Stimulation of soil organic matter fractions by maize straw return and nitrogen fertilization in the loess plateau of northwest China', *Applied Soil Ecology*, 191, p. 105061. Available at: https://doi.org/10.1016/j.apsoil.2023.105061.

Bei, S. *et al.* (2022) 'Nitrogen availability mediates the priming effect of soil organic matter by preferentially altering the straw carbon-assimilating microbial community', *Science of the Total Environment*, 815, p. 152882. Available at: https://doi.org/10.1016/j.scitotenv.2021.152882.

Bertini, S.C.B. *et al.* (2021) 'Soil physicochemical and biological profiles as indicators for araucaria forest disturbance levels', *Applied Soil Ecology*, 158, p. 103794. Available at: https://doi.org/10.1016/j.apsoil.2020.103794.

'Blake, G. R., & Hartge, K. H. (1986). Bulk Density. In A. Klute (Ed.), Methods of Soil Analysis Part 1. Physical and Mineralogical Methods (pp. 363-375). American Society of Agronomy, Inc.pdf' (no date).

Bremner, J.M. (1960) 'Determination of nitrogen in soil by the kjeldahl method', *Journal of Agricultural Science*, 55(1), pp. 11–33. Available at: https://doi.org/10.1017/S0021859600021572.

Brown, R.W. and Jones, D.L. (2024) 'Plasticity of microbial substrate carbon use efficiency in response to changes in plant carbon input and soil organic matter status', *Soil Biology & Biochemistry*, 188, p. 109230. Available at: https://doi.org/10.1016/j.soilbio.2023.109230.

Chang, F. *et al.* (2023) 'Once-middle amount of straw interlayer enhances saline soil quality and sunflower yield in semi-arid regions of China: Evidence from a four-year experiment', *Journal of Environmental Management*, 344, p. 118530. Available at: https://doi.org/10.1016/j.jenvman.2023.118530.

Delgado-Baquerizo, M. *et al.* (2016) 'Microbial diversity drives multifunctionality in terrestrial ecosystems', *Nature Communications*, 7(1), p. 10541. Available at: https://doi.org/10.1038/ncomms10541.

Delgado-Baquerizo, M. *et al.* (2016) 'Relative importance of soil properties and microbial community for soil functionality: Insights from a microbial swap experiment', *Functional Ecology*. Edited by E. Allen, 30(11), pp. 1862–1873. Available at: https://doi.org/10.1111/1365-2435.12674.

Delgado-Baquerizo, M. *et al.* (2020) 'Multiple elements of soil biodiversity drive ecosystem functions across biomes', *Nature Ecology & Evolution*, 4(2), pp. 210–220. Available at: https://doi.org/10.1038/s41559-019-1084-y.

Díaz-González, M., González-García, M.B. and Costa-García, A. (2005) 'Recent advances in electrochemical enzyme immunoassays', *Electroanalysis*, 17(21), pp. 1901–1918. Available at: https://doi.org/10.1002/elan.200503357.

Dick, W.A. *et al.* (2013) 'Prediction of β-glucosidase and β-glucosaminidase activities, soil organic C, and amino sugar N in a diverse population of soils using near infrared reflectance spectroscopy', *Soil Biology & Biochemistry*, 56, pp. 99–104. Available at: https://doi.org/10.1016/j.soilbio.2012.04.003.

Ding, K. *et al.* (2024) 'Long-term cover crop monocultures and mixtures improve soil multifunctionality and shift

microbial communities and functions', *European Journal of Agronomy*, 157, p. 127188. Available at: https://doi.org/10.1016/j.eja.2024.127188.

FAO. (2018). Global Livestock Environmental Assessment Model Model Description Version 2.0. Food and Agricultural Organisation of the United Nations (FAO) report. Available online at httpswww.fao.orgfileadminuser.pdf' (no date).

Feigl, V. *et al.* (2017) 'Influence of red mud on soil microbial communities: Application and comprehensive evaluation of the biolog EcoPlate approach as a tool in soil microbiological studies', *Science of the Total Environment*, 595, pp. 903–911. Available at: https://doi.org/10.1016/j.scitotenv.2017.03.266.

Hao, M. *et al.* (2019) 'Shifts in microbial community and carbon sequestration in farmland soil under long-term conservation tillage and straw returning', *Applied Soil Ecology*, 136, pp. 43–54. Available at: https://doi.org/10.1016/j.apsoil.2018.12.016.

Hu, M. *et al.* (2024) 'Contrasting effects of different straw return modes on net ecosystem carbon budget and carbon footprint in saline-alkali arid farmland', *Soil and Tillage Research*, 239, p. 106031. Available at: https://doi.org/10.1016/j.still.2024.106031.

Hu, N. *et al.* (2016) 'Effects of different straw returning modes on greenhouse gas emissions and crop yields in a rice–wheat rotation system', *Agriculture Ecosystems and Environment*, 223, pp. 115–122. Available at: https://doi.org/10.1016/j.agee.2016.02.027.

Huo, R. *et al.* (2024) 'Long-term straw return enhanced crop yield by improving ecosystem multifunctionality and soil quality under triple rotation system: An evidence from a 15 years study', *Field Crops Research*, 312, p. 109395. Available at: https://doi.org/10.1016/j.fcr.2024.109395.

Jayasudha, M.N., Reddy, M.K. and Bargali, S.S. (2024) 'Impact of cropping systems on macronutrient distribution and microbial biomass in drought affected soils'. Available at: https://doi.org/10.5194/egusphere-2024-40.

Kalayu, G. (2019) 'Phosphate solubilizing microorganisms: Promising approach as biofertilizers', *International Journal of Agronomy*, 2019, pp. 1–7. Available at: https://doi.org/10.1155/2019/4917256.

'Klute, A. (1986). Methods of Soil Analysis Part 1. Physical and Mineralogical Methods. American Society of Agronomy, Inc., 2nd edition.pdf' (no date).

Lal, R. (2004) 'Soil carbon sequestration impacts on global climate change and food security', *Science*, 304(5677), pp. 1623–1627. Available at: https://doi.org/10.1126/science.1097396.

Li, Jin *et al.* (2024) 'Deep return of straw improves topsoil health and maize productivity more efficiently than shallow return', *Soil Use and Management*, 40(4), p. e13131. Available at: https://doi.org/10.1111/sum.13131.

Li, X. *et al.* (2022) 'Synergistic effects of straw and earthworm addition on microbial diversity and microbial nutrient limitation in a subtropical conservation farming system', *Soil and Tillage Research*, 224, p. 105500. Available at: https://doi.org/10.1016/j.still.2022.105500.

Liu, B. *et al.* (2024) 'Straw addition enhances crop yield, soil aggregation, and soil microorganisms in a 14-year

wheat–rice rotation system in central China', *Plants*, 13(7), p. 985. Available at: https://doi.org/10.3390/plants13070985.

Liu, M., Lin, H. and Li, J. (2025) 'Are there links between nutrient inputs and the response of microbial carbon use efficiency or soil organic carbon? A meta-analysis', *Soil Biology & Biochemistry*, 201, p. 109656. Available at: https://doi.org/10.1016/j.soilbio.2024.109656.

Liu, Q. *et al.* (2024) 'Microbial community and functions depending on tillage and straw returning management: Consequences for soil health and ecosystem services', *Land Degradation and Development*, 35(17), pp. 5357–5366. Available at: https://doi.org/10.1002/ldr.5301.

Liu, R.-Z. *et al.* (2024) 'Effects of different straw return methods on soil properties and yield potential of maize', *Scientific Reports*, 14(1). Available at: https://doi.org/10.1038/s41598-024-70404-8.

Liu, S. *et al.* (2022) 'Composition and diversity of soil microbial community associated with land use types in the agro–pastoral area in the upper yellow river basin', *Frontiers in Plant Science*, 13, p. 819661. Available at: https://doi.org/10.3389/fpls.2022.819661.

Liu, X. *et al.* (2023) 'Straw return drives soil microbial community assemblage to change metabolic processes for soil quality amendment in a rice-wheat rotation system', *Soil Biology & Biochemistry*, 185, p. 109131. Available at: https://doi.org/10.1016/j.soilbio.2023.109131.

'Methods of Soil Analysis Part 2, Chemical and Microbiological Properties.pdf' (no date).

'Olsen SR, Sommers LE (1982) Phosphorus. In Page AL et al (eds) Methods of soil analysis. Part 2 Chemical and microbial properties, 2nd edn. ASA and SSSA, Madison, pp 401–430.pdf' (no date).

Pan, Y. *et al.* (2023) 'Carbon source shaped microbial ecology, metabolism and performance in denitrification systems', *Water Research*, 243, p. 120330. Available at: https://doi.org/10.1016/j.watres.2023.120330.

Peng, X.-X. *et al.* (2024) 'Effects of artificial humic acid on decomposition of returning straw and enhancement of carbon sequestration', *Applied Soil Ecology*, 203, p. 105619. Available at: https://doi.org/10.1016/j.apsoil.2024.105619.

Preston-Mafham, J., Boddy, L. and Randerson, P.F. (2002) 'Analysis of microbial community functional diversity using sole-carbon-source utilisation profiles – a critique', *FEMS Microbiology Ecology*, 42(1), pp. 1–14. Available at: https://doi.org/10.1111/j.1574-6941.2002.tb00990.x.

'Sanchez, G. (Ed.), 2013. PLS Path Modeling with R, Berkeley..pdf' (no date).

Shrivastava, P. and Kumar, R. (2015) 'Soil salinity: A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation', *Saudi Journal of Biological Sciences*, 22(2), pp. 123–131. Available at: https://doi.org/10.1016/j.sjbs.2014.12.001.

Song, J. *et al.* (2024) 'Subsurface organic amendment of a saline soil increases ecosystem multifunctionality and sunflower yield', *Science of the Total Environment*, 917, p. 170276. Available at: https://doi.org/10.1016/j.scitotenv.2024.170276.

Song, Y., Gao, M. and Li, Z. (2025) 'Impacts of straw return methods on crop yield, soil organic matter, and salinity in saline-alkali land in north China', *Field Crops Research*, 322, p. 109752. Available at: https://doi.org/10.1016/j.fcr.2025.109752.

'Tenenhaus, M., Amato, S., Esposito Vinzi, V., 2004. A global goodness-of-fit index for PLS structural equation modelling. In Proceddings of the XLII SIS Scientific Meeting, pp, 739-742. Padova..pdf' (no date).

Tian, Y. *et al.* (2025) 'Are adding carbon sources and activated sludge helpful to the full-scale packing-reinforced multistage biological contact oxidation process?', *Journal of Environmental Management*, 376, p. 124461. Available at: https://doi.org/10.1016/j.jenvman.2025.124461.

Vizioli, B. *et al.* (2021) 'Effects of long-term tillage systems on soil physical quality and crop yield in a brazilian ferralsol', *Soil and Tillage Research*, 209, p. 104935. Available at: https://doi.org/10.1016/j.still.2021.104935.

Walkley, A. and Black, I.A. (1934) 'An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method':, *Soil Science*, 37(1), pp. 29–38. Available at: https://doi.org/10.1097/00010694-193401000-00003.

Wang, L.-Q. *et al.* (2024) 'Regulation of tillage on grain matter accumulation in maize', *Frontiers in Plant Science*, 15, p. 1373624. Available at: https://doi.org/10.3389/fpls.2024.1373624.

Wang, X. *et al.* (2024) 'Straw return can increase maize yield by regulating soil bacteria and improving soil properties in arid and semi-arid areas', *European Journal of Agronomy*, 161, p. 127389. Available at: https://doi.org/10.1016/j.eja.2024.127389.

Wei, H. *et al.* (2023) 'Improved soil composition promotes nutrient recovery during vegetation restoration in karst peak-cluster depressions', *Catena*, 222, p. 106769. Available at: https://doi.org/10.1016/j.catena.2022.106769.

Wei, L. *et al.* (2025) 'Effects of straw returning after anaerobic microbial pretreatment on soil carbon sequestration and emission reduction', *Environmental Technology & Innovation*, 38, p. 104124. Available at: https://doi.org/10.1016/j.eti.2025.104124.

Wen, L. *et al.* (2023) 'Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis', *Journal of Environmental Management*, 345, p. 118904. Available at: https://doi.org/10.1016/j.jenvman.2023.118904.

Xiao, D. *et al.* (2022) 'Network analysis reveals bacterial and fungal keystone taxa involved in straw and soil organic matter mineralization', *Applied Soil Ecology*, 173, p. 104395. Available at: https://doi.org/10.1016/j.apsoil.2022.104395.

Yan, Y. *et al.* (2022) 'Quantification of the effects of long-term straw return on soil organic matter spatiotemporal variation: a case study in typical black soil region'. Available at: https://doi.org/10.5194/egusphere-2022-963.

Yao, R. *et al.* (2023) 'Deep vertical rotary tillage mitigates salinization hazards and shifts microbial community structure in salt-affected anthropogenic-alluvial soil', *Soil and Tillage Research*, 227, p. 105627. Available at: https://doi.org/10.1016/j.still.2022.105627.

Yin, W. *et al.* (2023) 'No-tillage with straw mulching boosts wheat grain yield by improving the eco-physiological characteristics in arid regions', *Journal of Integrative Agriculture*, 22(11), pp. 3416–3429. Available at: https://doi.org/10.1016/j.jia.2023.02.041.

Zhang, P. *et al.* (2025) 'Balancing soil carbon emissions and productivity in maize agroecosystems through nitrogen, biochar, and straw regulation', *Industrial Crops and Products*, 224, p. 120442. Available at: https://doi.org/10.1016/j.indcrop.2024.120442.

Zhang, S. *et al.* (2025) 'Broad-spectrum applications of plant growth-promoting rhizobacteria (PGPR) across diverse crops and intricate planting systems', *Microbiology Spectrum*. Edited by C.G.B. Banaay, 13(3), pp. e01879-24. Available at: https://doi.org/10.1128/spectrum.01879-24.

Zhang, X. *et al.* (2023) 'Effects of tillage on soil organic carbon and crop yield under straw return', *Agriculture Ecosystems and Environment*, 354, p. 108543. Available at: https://doi.org/10.1016/j.agee.2023.108543.

Zhang, X. *et al.* (2024) 'Nitrogen and straw management for sustainable maize-wheat cropping in the north China plain: Insight from crop yield and nitrogen use efficiency', *Journal of Soil Science and Plant Nutrition*, 24(1), pp. 922–934. Available at: https://doi.org/10.1007/s42729-023-01596-7.

Zhou, H. *et al.* (2020) 'Evaluation of straw spatial distribution after straw incorporation into soil for different tillage tools', *Soil and Tillage Research*, 196, p. 104440. Available at: https://doi.org/10.1016/j.still.2019.104440.

Zhou, T. *et al.* (2024) 'The heterogeneous habitat of taiga forests changes the soil microbial functional diversity', *Microorganisms*, 12(5), p. 959. Available at: https://doi.org/10.3390/microorganisms12050959.

'Zhou, Y., Ma, H. B., Xie, Y. Z., Jia, X., Su, T., Li, J., et al. (2020). Assessment of soil quality indexes for different land use types in typical steppe in the loess hilly area, China. Ecolog. Indicat. 118, 10674.pdf' (no date).

Zhu, M. *et al.* (2024) 'Time-dependent regulation of soil aggregates on fertilizer N retention and the influence of straw mulching', *Soil Biology & Biochemistry*, 198, p. 109551. Available at: https://doi.org/10.1016/j.soilbio.2024.109551.

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