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The Effects of Natural Humus Material Amendment on Soil Organic Matter and Integrated Fertility in the Black Soil of Northeast China: Preliminary Results

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Abstract: The input of exogenous organic materials is an effective way to improve soil organic matter (SOM) content in cropland. The exploration of the impact of new organic materials such as woody peat on black soil fertility can provide an important reference for preventing the degradation of black soil in Northeast China. In this study, the effects of adding woody peat to SOM and the soil-integrated fertility of black cropland were studied by seven treatments (no organic matter addition, CK; crop straw returning, SR; decomposed straw addition, DS; organic manure addition, OM; 6 t/ha woody peat addition, LWP; 10.5 t/ha natural humus material addition, MWP; and 15 t/ha natural humus material addition, HWP). The results show that natural humus material additions (LWP, MWP, and HWP treatments) could significantly increase SOM (increased by 4.79~9.41 g/kg), labile SOM (increased by 2.49~4.52 g/kg), and recalcitrant SOM (increased by 2.13~6.39 g/kg) components, respectively. For comparison, traditional organic material inputs (SR, DS, and OM treatments) had no significant effect on SOM but induced an increase in the labile SOM component in the following year. This study also found that natural humus material additions could improve soil-integrated fertility in a year term, especially in promoting SOM accumulation. However, organic manure amendment showed both the advantage of increasing soil fertility slightly and the disadvantage of increasing soil salt sharply. In conclusion, compared with traditional exogenous organic materials, the natural humus material amendment technique can rapidly increase the total SOM quantity and its different stability components and has a great effect in improving the integrated fertility of black soil. Thus, it is of significance to further study the potential of natural humus material amendment in the fertility of black soil in future.

Keywords: natural humus material; straw returning; organic matter; black soil; organic manure; soil-integrated fertility

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1. Introduction

According to the Global Soil Partnership (GSP) of the Food and Agriculture Organization of the United Nations (FAO), high organic matter is a typical characteristic of black soils. The innate high natural fertility of such soils makes them important in global agricultural development [1]. Thus, black cropland is a unique treasure given by nature to human beings known as the "giant panda in arable land" in China. As one of the four

remaining black soil regions in the world, the black soil region in Northeast China is the most important commodity grain-producing area in China [2]. According to past reports, due to the constraints of natural factors and high-intensity artificial utilization, the surface thickness of the black soil in the black soil area has been significantly reduced, and the surface thickness of some areas is less than 30 cm [3,4]. Black soil is facing the risk of losing its productive capacity and even the disappearance of the black soil layer [3–5]. How to prevent the degradation of black soil has become one of the important topics in the study of black land protection.

As the vital organic component in soil, soil organic matter (SOM) plays an important role in soil basal fertility [6]. Throughout the evolution characteristics of black soil fertility, natural vegetation was transformed into crops, and agricultural production activities removed the aboveground part of crops from the soil ecosystem, which greatly reduced the input of exogenous organic residues to the soil since the reclamation of black land. Thus, SOM consumption was much higher than the accumulation under high-intensity agricultural production conditions. In the northeast of China, the first 40 years of black land reclamation were considered as the reclamation and utilization stage. At the initial stage of reclamation, the SOM content decreased sharply [3]. However, the soil nitrogen, phosphorus, and potassium nutrients gradually tended to the proportion of crop demand, showing the synchronous increase in soil fertility and productivity (that is, soil ripening). However, the SOM content gradually decreased with the increasing production demand. Up to now, the SOM content of black soil has decreased by about 2/3, and the loess parent material is even exposed in some areas, facing the risk of black soil disappearing [3,4]. It can be seen that the black soil carbon pool is constantly in a state of being a "carbon source". Numerous studies have confirmed that organic fertilization practices, such as organic fertilizer and straw returning, could prevent the degradation of black soil and increase the accumulation of SOM in the last few decades [7,8].

At present, the mainstream view of increasing soil organic compensation has become one of the key contents to prevent the decline in black soil [4]. Exogenous organic matter input has long been regarded as an effective way to improve soil fertility, such as crop straw turnover, organic manure, or green manure applications [8–11]. These carbon-containing organic materials can play the main function of plant nutrition when applied into soil [12]. Meanwhile, exogenous organic materials applied to soil are first assimilated and utilized by microorganisms to become microbial biomass, which is beneficial to accelerate the turnover process of microbial biomass [13,14]. With the continuous input of exogenous organic materials over the years, the living microbial biomass maintained a continuous and rapid turnover, and a large number of microbial residues were continuously produced. As a final result, the secreted substances and microbial residues metabolized by microorganisms eventually become an important part of stable SOM [13]. It is worth noting that the efficiency of this method of organic amendment is still low, and it usually takes several years for SOM accumulation to increase dramatically only through the input of exogenous organic materials according to previous long-term field experiments [9]. Some studies also reported that straw nutrients are released quickly and have a low utilization rate, which makes it difficult to promote SOM accumulation in a short time [15,16]. In addition, organic fertilizer practices also have shortcomings. For example, Guo et al. [17] and Xie et al. [18] reported that the long-term application of organic fertilizer leads to the increase in soil sodium ions, which has the potential risk of salinization and is not conducive to the stability of the soil structure. Therefore, in order to find a more ideal material for improving soil fertility, some scholars tried to add woody peat-based amendment to the farmland so as to achieve both the rapid increase in SOM content and for the purpose of rapid fertilization. Woody peat is a kind of stable organic matter which is not easy to decompose and is formed after the long-term accumulation of woody plant residues in humid and anaerobic environments. The humus content of woody peat is 30~41 times that of soil and 4~5 times that of organic fertilizer. Moreover, the humification degree of the organic matter of woody peat is much higher than that of organic fertilizer, indicating that it has the best

stability in soil. Zheng et al. [19] proved that woody peat is an ideal improvement material superior to organic fertilizer because woody peat has a high organic carbon content and can rapidly increase SOM when it is applied to soil. Some other researchers also revealed that woody peat addition could increase the SOM concentration in cropland in a short time and is environmentally friendly to the soil [20–22]. The results of these reported studies have important reference value for revealing the potential of woody peat to rapidly increase soil organic carbon stock and improve soil properties. However, studies on the use of woody peat for soil improvement are still very limited, especially on degraded black soil.

In addition, although concern about the addition of exogenous organic materials (crop straw, organic manure, etc.) has generated much research on integrated soil fertility management [12,17,23], there is a lack of understanding of the application of natural humus material for increasing soil fertility and crop productivity. As natural organic matter, woody peat has similar homology to soil organic matter. Naturally, the addition of natural humus material can rapidly increase the soil organic matter content quantitatively, but its overall effect on soil fertility remains unclear. Previous studies have revealed that soil-integrated fertility changes can be comprehensively reflected by judging soil property indexes, such as SOM components, nitrogen, phosphorus, potassium, pH, soil electrical conductivity (EC), etc. For example, Zhang et al. [24] suggested that soil chemical properties (SOM, total nitrogen and phosphorus) could reflect soil fertility characteristics with poor structure. In addition to SOM, nitrogen, phosphorus, potassium, and other nutrient elements, soil pH and EC changes could reveal the negative effects of exogenous organic matter additions [17,25]. Therefore, it is necessary to comprehensively study the response of soil properties, such as SOM, nitrogen, phosphorus and potassium, pH, bulk density, EC, etc., to the addition of natural humus materials, which may be of significance for the comprehensive evaluation of the effects of natural humus materials on soil fertility.

This study aimed to investigate the effects of natural humus material, crop straw, and organic manure on black soil fertility. Natural humus material was selected as soil conditioner for improving soil fertility, and contrast analysis of the effects of decomposed straw, organic fertilizer, and straw returning on soil-integrated fertility was also carried out. Results from this study will provide unique insights to prevent the degradation of the black soil.

2. Materials and Methods

2.1. Site Description

This study was conducted at a demonstration experimental field (latitude 47°32′ N, longitude 130°35′ E, elevation of 111 m) situated in Northeast China. The field experiment began in March 2021. The area has a temperate continental monsoon climate with an average annual temperature of 1.57 °C, a frost-free period of 128 days, and an annual precipitation of about 549 mm. Prior to the start of the experiment, the soil in the plow layer (0–20 cm) had a bulk density of 1.59 g/cm^3 and contained SOM of 35.67 g/kg, total nitrogen of 1.57 g/kg, total phosphorus of 1.27 g/kg, total potassium of 22.18 g/kg, alkaline nitrogen of 103.24 mg/kg, available phosphorus of 68.95 mg/kg, and available potassium of 306.50 mg/kg. The soil type is black soil, and it had a coarse sandy loam texture with 41.9% sand, 50.5% silt, and 7.6% clay and an average pH of 5.72 in March 2021.

2.2. Experimental Design and Agronomic Management

The experiment included seven treatments: control (CK; no exogenous materials addition) plots, straw-returning (SR; 7.5 t/ha crop straw returning) plots, decomposed straw (DS; 3 t/ha decomposed straw addition) plots, organic manure (OM; 7.5 t/ha organic manure addition) plots, low natural humus material conditioner (LWP; 6 t/ha natural humus material addition) plots, moderate natural humus material conditioner (MWP; 10.5 t/ha natural humus material addition) plots, and high natural humus material conditioner (HWP; 15 t/ha natural humus material addition) plots. Each treatment applied 400 kg/ha of chemical synthetic fertilizer. In addition, the above exogenous materials were only applied once before the experiment (i.e., April 2021). In the second year, all the treatments

were applied to the same conventional soil management practices (including mechanical rotary tillage 0–20 cm, crop stubble return to field, and the same crop management), and the amount of fertilizer applied was 400 kg/ha, and no decomposed straw, organic fertilizer, or natural humus material was added.

The natural humus material used in this study was made of woody peat material by View Sino Orise Technology Co., Ltd. (Jiangyin, China). The decomposed straw and organic manure were made of corn straw after 120 days of high temperature fermentation and animal waste, respectively. The properties of the different organic materials are shown in Table 1. The above applied materials and fertilizers were evenly mixed into 0–20 cm topsoil by mechanical rotary tillage before sowing. The chemical synthetic fertilizer used in this study contained 20.5% N, 23% P_2O_5, and 15% K_2O.

Table 1. Properties of different organic materials.

Name	SOM (%)	Total Nitrogen (g/kg)	Total P_2O_5 (g/kg)	Total K_2O (g/kg)	pH	EC (μs/cm)
Crop straw	78.1	9.8	4.8	19.8	/	/
Decomposed straw	45.4	21	11	22	7.4	1800
Organic manure	36.5	23.1	1.71	58.9	7.9	2100
Natural humus material	89	6.8	0.09	0.18	5.4	92.8

Each treatment was set with three replicates, and the area of each plot was 510 m^2. Each plot was randomly arranged. Only single-season corn crops were planted from April to October each year. The maize variety was 'Xianyu 1219', and it was sown on 5 May and harvested on 10 October. Topsoil samples were collected at the maturing stage of the crops for soil index analysis, and the yields of maize were also measured.

2.3. Soil Sampling and Analysis

Three intact soil cores (0–20 cm) from each plot were collected using a 12 cm wide sampling stainless steel shovel and then mixed to form one composite sample on 10 October 2021 and 1 October 2022, respectively. The moist samples were immediately transferred in hard plastic boxes to the laboratory.

Moist soil samples were gently broken apart along natural break points and passed through a 10 mm sieve. Plant and organic debris in the sieved soil was carefully identified, visually, and removed with forceps. After mixing thoroughly, a subsample of the 10 mm sieved soil was further passed through a 2 mm sieve and then used to determine the dissolved organic matter (DOM). Another subsample of the 10 mm sieved soil was also further passed through a 2 mm sieve and then was air dried indoors. The air-dried soil samples were used to determine the SOM, labile organic matter (LOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkalyzable nitrogen (AN), available phosphorus (AP), and available potassium (AK) contents, pH, and soil electrical conductivity (EC), respectively.

The SOM content was measured by the wet redox titration method and the potassium permanganate oxidation method, respectively [26,27]. Briefly, about 250.0 mg of soil (accurate 1/10 mg) was placed in a digestive tube with 5 mL of 0.8 mol/L $K_2Cr_2O_7$ and 5 mL of H_2SO_4 after boiling for 5 min in a graphite digestion meter at 185 °C. The remaining Cr^{6+} was determined using 0.2 mol/L $FeSO_4$ with an *o*-phenanthroline indicator. The carbon oxidized by hexavalent chromium was regarded as soil organic carbon. According to the proportion of 58% carbon in the SOM, the organic carbon content was converted to SOM content. About 2.5 g soil was weighed in a 50 mL centrifuge tube, and 25 mL of 333 mmol/L $KMnO_4$ was added. The mixture was oscillated back and forth for 30 min at 180 rpm. Then, these samples were centrifuged for 10 min at 2500 rpm after standing for 15 min. The concentration of the supernatant was determined with a spectrophotometer (at 565 nm wave). The amount of oxidizing agent consumed by $KMnO_4$ was used to calculate the LOM. The difference in the SOM and LOM was used as the recalcitrant SOM component (AOM). The determined dissolved organic matter (DOM) was extracted with distilled water.

Briefly, soil DOM was extracted from the soil by shaking fresh soil samples with double-distilled water (V/W = 2:1) for 30 min followed by centrifugation for 10 min (4000 rpm). The supernatant was filtered through a 0.45 μm filter. The extracts were then analyzed for DOM by the wet redox titration method. The total nitrogen and AN were determined by the semimicro Kjeldahl and alkaline hydrolysis diffusion methods, respectively [26]. The TP was determined by molybdenum blue colorimetry. Additionally, the AP was extracted with 0.5 mol/L $NaHCO_3$ and determined using the molybdenum blue method [28]. TK and AK contents were determined using a flame photometer. Briefly, the soil TK and AK were determined by the HF-$HClO_4$ digestion method and the ammonium acetate extraction method, respectively [29]. The soil pH was determined in a soil:distilled water mixture (1:2.5; CO_2 removed) with a pH probe. The soil EC was determined by ammonium acetate exchange using the atomic absorption spectrophotometry method [29].

2.4. Soil Fertility Index

Soil properties, including SOM, LOM, AOM, DOM, TN, TP, TK, AN, AP, AK, pH, and EC, were considered in the soil fertility. Five steps were executed to evaluate the integrated soil fertility according Shukla et al. [30] and Zhang et al. [24]: (1) extracting the factors from the measured soil attributes using the method of principal components; (2) performing the varimax with Kaiser normalization for rotation to minimize the number of variables with the highest loading in each factor and thus to simplify the interpretation of the factors; (3) selecting the representative principal components to establish the minimum dataset through the factor analysis technique; (4) scoring the integrated indicators in the minimum dataset according to a regression method; and (5) integrating the scores of indicators into a comparative index for soil fertility based on their weight factors. Factors with eigenvalues >1.0 and those that explain at least 5% of the variation in the dataset were selected as the representative principal components. The individual percentages of total variation in the total dataset explained by the representative principal components were termed as their weight factors.

The scoring function was used to calculate the scores of indicators in the minimum dataset and their integrated score:

$$Z_i = r_{i1}x_1 + r_{i2}x_2 + \cdots + r_{ij}x_j + \cdots + r_{ip}x_p$$
$$F = \sum w_i Z_i$$

where Z_i is the score of the ith integrated indicator in the minimum data set; x_j is the normalization for the jth measured soil attribute derived from the factor analysis (j = 1, 2, … p); r_{ij} is the component score coefficient matrix that could be directly obtained by the factor analysis; w_i is the weighting factor for the ith integrated indicator; and F is the integrated score of all indicators in the minimum dataset, and it is regarded as the soil fertility index. Higher F values were assumed to mean better soil fertility.

2.5. Statistical Analysis

Statistical analysis was performed with the SPSS 22.0 software package for Windows (SPSS Inc., New York, NY, USA). One-way ANOVA was used to test for significant differences in the various measured parameters ($p < 0.05$) among the different treatments using the least significant difference (LSD) to compare between means.

3. Results

3.1. Effects of Different Treatments on SOM and Its Components

As the material base of soil nutrition, SOM directly reflects the level of soil fertility. As shown in Figure 1, compared to CK treatment, SOM content in the LWP, MWP, and HWP treatments were increased by 4.79~5.06 g/kg, 6.00~6.58 g/kg, and 9.36~9.41 g/kg from 2021 to 2022, respectively. In 2021, only the SOM content of the HWP treatment increased significantly, but in 2022, LWP, MWP, and HWP all increased significantly. While the SOM content in the SR, DS, and OM treatments increased obviously, it did not reach the

level of significant difference ($p < 0.05$). Although the SOM content treated by SR and OM increased substantially in the first year, it appeared to decrease in the second year. From the observation data of two years, the total SOM quantity of natural humus material-adding treatments (LWP, MWP and HWP) was stable, and the effect difference was more significant in the second year compared with conventional soil fertility-improving practices (SR, DS, and OM treatments) and CK according to difference analysis (Figure 1).

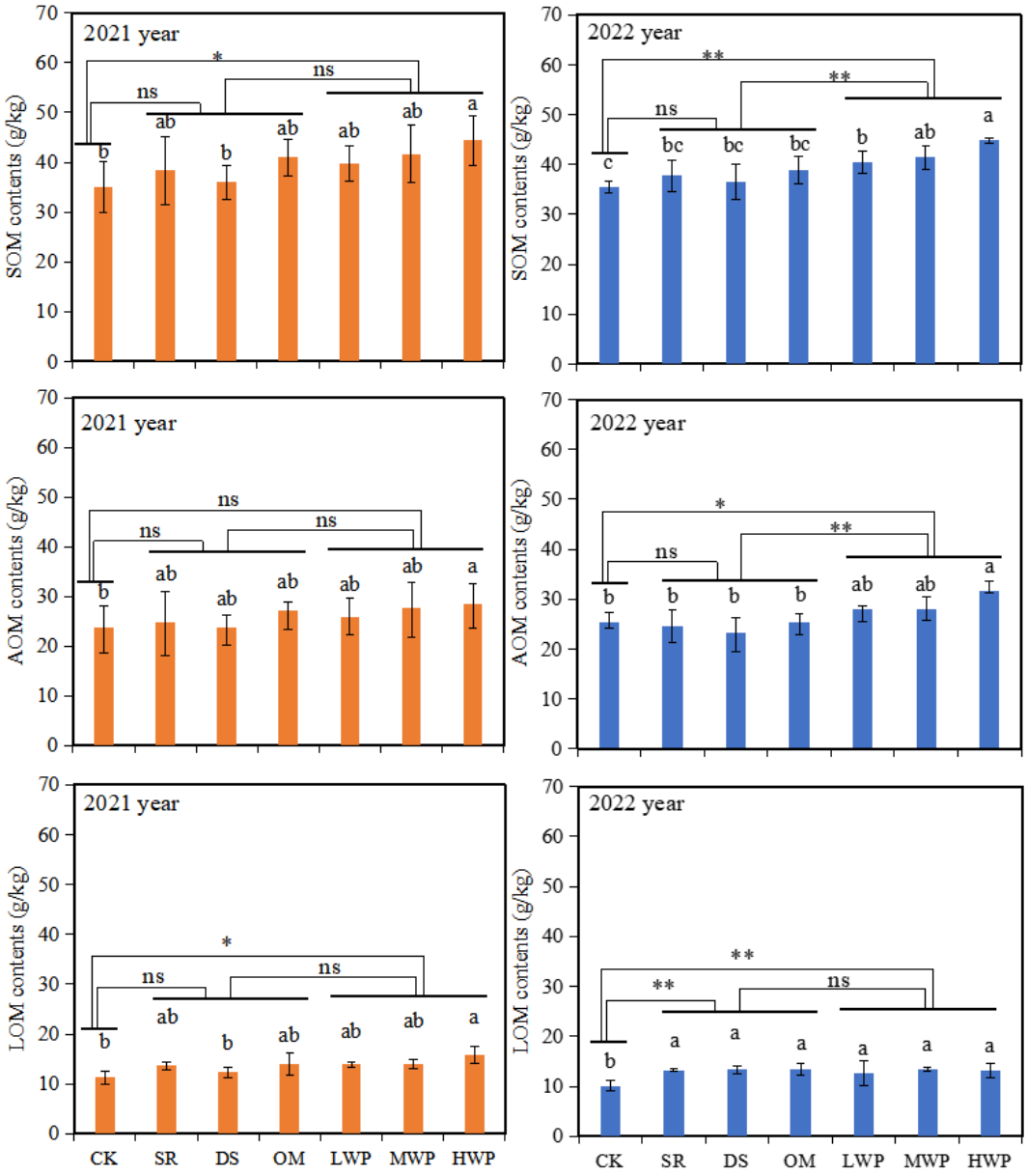


Figure 1. Changes in soil organic matter (SOM), labile organic matter (LOM), and recalcitrant organic matter (AOM) contents under different treatments. Vertical bars denote the standard error of the mean ($n = 3$). Different letters, a, b, and c, indicate significant differences between treatments for the same histogram at $p < 0.05$. Significant differences among CK, conventional soil fertility-improving practices (SR, DS, and OM treatments), and natural humus material-adding treatments (LWP, MWP, and HWP) are indicated by * $p < 0.05$ and ** $p < 0.01$. ns represents no statistical significance at the $p \geq 0.05$ level.

As the active component of SOM, LOM is regarded as an early indicator of the change in the total SOM [31]. AOM a has high stability, which determines the soil carbon

storage [32]. Thus, studying the changes in LOM and AOM can further reveal the soil carbon pool and its variation characteristics. Compared to CK, HWP treatment significantly enhanced LOM and AOM contents by 3.01~4.52 g/kg and 4.84~6.39 g/kg, respectively. However, only the LOM content of conventional soil fertility-improving practices (SR, DS and OM treatments) increased significantly in 2022 (Figure 1). DOM is treated as the most active component of SOM and plays an important role in regulating soil biochemical cycling [33,34]. The results in Figure 2 show that the DOM content of the HWP, OM, and DS treatments was significantly higher, 60.60 mg/kg, 54.35 mg/kg, and 17.31 mg/kg, than that of CK in 2021, respectively, while SR, LWP, and MWP treatments had no significant effect on DOM when compared to CK. The characteristics of DOM changes in 2022 were similar to those in 2021, except in that of the DS treatment. which showed a significant decline (decreased by 0.14 g/kg) (Figure 2).

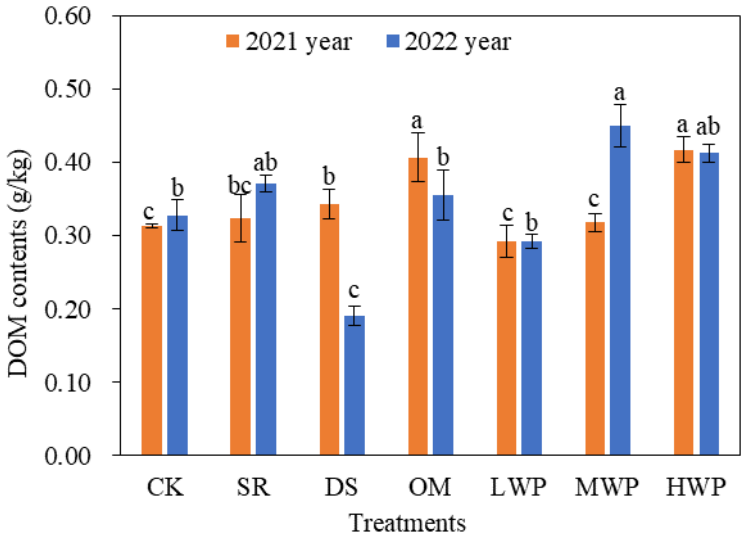


Figure 2. Changes in soil dissolved organic matter (DOM) content under different treatments in 2021 and 2022. Vertical bars denote the standard error of the mean (n = 3). Different letters, a, b, and c, indicate significant differences between treatments in the same year at $p < 0.05$.

3.2. Effects of Different Treatments on Soil NPK Content

Because the nutrient elements of NPK are closely related to crop growth and soil fertility, soil NPK is often used as an important index to evaluate soil fertility. As shown in Figure 3, in 2021, the SR and DS treatments decreased in TN and TP contents when compared to CK but did not reach a significant level ($p < 0.05$). Compared to CK, the OM treatment significantly increased the TN content (by 0.22 g/kg) but had no significant effect on TP and TK. The LWP, MWP, and HWP treatments also had no significant effects on TN, TP, and TK. In addition, compared to CK, the SR and DS treatments decreased in AN, AP, and AK slightly. However, OM treatment slightly enhanced AN (by 25.11 mg/kg), AP (by 4.29 mg/kg), and AK (by 22.67 mg/kg) contents. As a whole, the effects of different treatments on soil AN, AP, and AK did not reach the level of significant difference ($p < 0.05$).

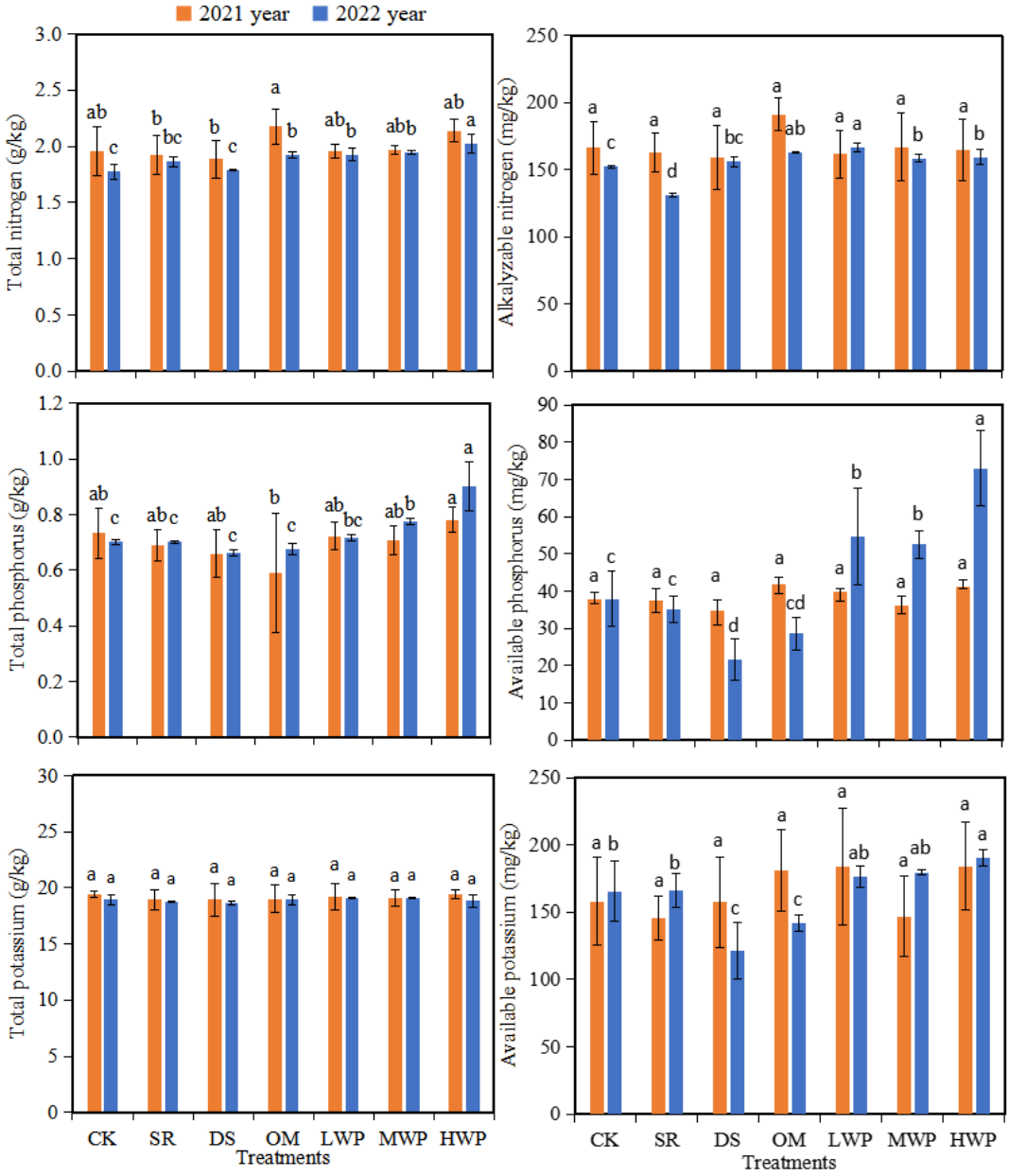


Figure 3. Changes in the total nitrogen (TN), phosphorus (TP), and potassium (TK) contents and the available nitrogen (AN), phosphorus (AP), and potassium (AK) contents in topsoil under different treatments. Different lowercase letters in the same box denote significant differences between different treatments of the same year at $p < 0.05$, respectively.

In 2022, the variation characteristics of the TN, TP, and TK contents in different treatments were similar to those in 2021, but the data difference between treatments was more significant than that in 2021. Specifically, the AP content of natural humus material-adding treatments (LWP, MWP, and HWP) was significantly higher than other treatments, but the AK content in DS and OM treatments decreased significantly when compared to other treatments (Figure 3).

3.3. Effects of Different Treatments on Soil pH and EC

The variation characteristics of soil pH and EC in 2021 and 2022 were consistent (Figures 4 and 5). The results of this study show that OM treatment significantly decreased soil pH when compared to CK. Meanwhile, the addition of straw (SR and DS treatments)

and natural humus material (LWP, MWP, and HWP treatments) had no significant effects on soil pH (Figure 4). Compared to CK, OM had the highest EC value, followed by HWP treatment. However, other treatments had no significant effects on the soil EC (Figure 5).

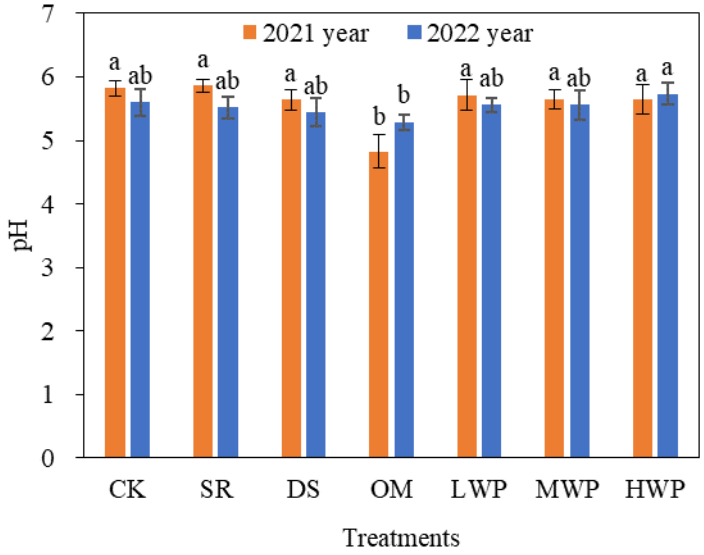


Figure 4. Changes in soil pH under different treatments. Different lowercase letters in the box denote significant differences between different treatments of the same year at $p < 0.05$, respectively.

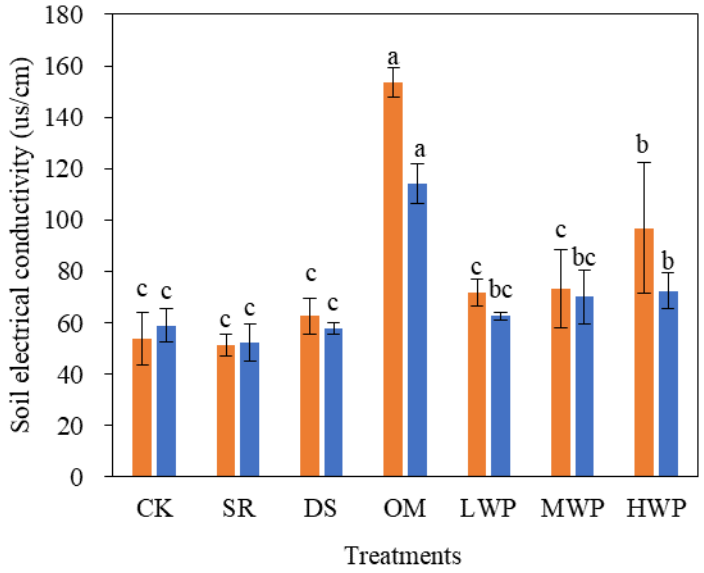


Figure 5. Changes in soil electrical conductivity (EC) under different treatments. Different lowercase letters in the box denote significant differences between different treatments of the same year at $p < 0.05$, respectively.

3.4. Changes in Maize Yield under Different Treatments

In terms of yield, HWP treatment had the highest maize yield, followed by the SR, OM, LWP, and MWP treatments. Moreover, CK and the DS treatment had the lowest maize yields (Figure 6). In general, only HWP treatment had a significant promoting effect on yield with an increase rate of about 5.97% in 2021 and 20.32% when compared to CK, respectively.

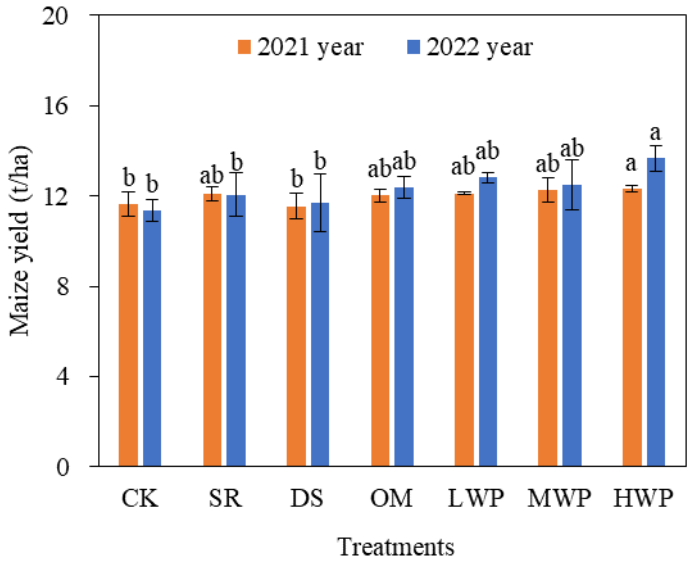


Figure 6. Change in maize yield under different treatments. Different lowercase letters in the box denote significant differences between different treatments of the same year at $p < 0.05$, respectively.

3.5. Changes in Integrated Fertility under Different Treatments

In 2021, the results of factor analysis showed that three main factors were obtained by principal component analysis which could explain 42.54%, 19.58%, and 9.52% of the total variance in the variables, respectively. Moreover, the cumulative variance of the three main factors reached 71.65%. Meanwhile, in 2022, the dimensions of all observed variables were reduced to four main factors which could explain 82.44% of the total variance in all variables. According to the size of the variable loading coefficients, SOM, TN, and TP in principal components 1 and 2 had the largest load coefficients (greater than 0.8) in 2021, while SOM, AOM, TP, AK, and AP in principal component 1, EC in principal component 2, and TK in principal component 3 had the highest load coefficients (greater than 0.8) (Tables 2 and 3). Thus, SOM and TN made a great contribution to factor 1, TP and pH made a great contribution to factor 2, and AK made a great contribution to factor 3 in 2021 (Table 2). Similarly, SOM, AOM, TP, AK, and AP made a great contribution to the integrated fertility in 2022 (Table 3).

Table 2. Variable loading coefficients of the first three factors extracted using soil properties and communality in 2021.

Variable	Factor 1	Factor 2	Factor 3	Communality
SOM	0.85	0.28	0.23	0.86
LOM	0.75	0.30	0.11	0.66
AOM	0.79	0.27	0.22	0.74
DOM	0.63	−0.29	0.23	0.53
TN	0.86	−0.18	0.24	0.83
TP	0.03	0.81	0.28	0.73
TK	0.24	0.41	0.03	0.22
AN	0.68	−0.21	0.18	0.54
AP	0.67	0.47	−0.44	0.86
AK	0.50	0.36	−0.74	0.93
pH	−0.64	0.70	0.16	0.92
EC	0.72	−0.50	−0.24	0.83
Eigenvalue	5.19	2.31	1.15	8.65
Component variance (%)	43.24	19.27	9.61	72.12
Cumulative variance (%)	43.24	62.51	72.12	

Table 3. Variable loading coefficients of the first three factors extracted using soil properties and communality in 2022.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Communality
SOM	0.88	0.25	−0.12	0.18	0.89
LOM	0.16	0.50	0.09	0.76	0.86
AOM	0.91	0.05	−0.18	−0.16	0.88
DOM	0.68	−0.05	0.45	0.19	0.70
TN	0.79	0.34	−0.31	0.12	0.85
TP	0.85	−0.11	−0.34	−0.03	0.85
TK	0.30	0.22	0.86	−0.16	0.90
AN	0.23	0.67	−0.03	−0.59	0.85
AK	0.92	−0.14	0.03	−0.12	0.88
AP	0.83	−0.35	0.23	−0.04	0.86
pH	0.65	−0.55	0.03	−0.01	0.73
EC	0.09	0.80	0.02	−0.07	0.65
Eigenvalue	5.54	2.02	1.26	1.08	9.89
Component variance (%)	46.14	16.85	10.49	8.96	82.44
Cumulative variance (%)	46.14	62.99	73.48	82.44	

Furthermore, the integrated fertility scores of different treatments showed that HWP treatment had the highest scores (0.608 in 2021 and 0.67 in 2022), followed by the SR, OM, LWP, and MWP treatments (−0.13~0.20 in 2021 and −0.23~0.46 in 2022). Meanwhile, CK and DS had the lowest scores (−0.34~−0.32 in 2021 and −0.66~−0.49 in 2022), which were significantly lower than that of HWP (Tables 4 and 5).

Table 4. Principal component scores and integrated fertility scores of soil fertility under different treatments in 2021.

Treatments	Factor 1	Factor 2	Factor 3	Integrated Fertility Scores
CK	−0.8	0.2	−0.15	−0.32 b
SR	−0.52	0.29	0.4	−0.13 ab
DS	−0.63	−0.28	−0.1	−0.34 b
OM	1.05	−1.13	−0.37	0.20 ab
LWP	−0.15	0.61	−0.56	−0.00 ab
MWP	−0.14	0.12	0.54	0.01 ab
HWP	1	0.63	0.58	0.61 a

Different lowercase letters in the same column denote significant differences between treatments at $p < 0.05$, respectively.

Table 5. Principal component scores and integrated fertility scores of soil fertility under different treatments in 2022.

Treatments	Factor 1	Factor 2	Factor 3	Factor 4	Integrated Fertility Scores
CK	−0.52	−1.13	0.51	−1.24	−0.49 c
SR	−0.42	−1.11	0.12	1.58	−0.23 bc
DS	−1.33	0.08	−0.76	0.22	−0.66 c
OM	−0.44	1.79	0.16	0.01	0.12 b
LWP	0.33	0.20	0.21	−0.85	0.13 b
MWP	0.72	0.22	0.62	0.28	0.46 ab
HWP	1.66	−0.06	−0.87	0.01	0.67 a

Different lowercase letters in the same column denote significant differences between treatments at $p < 0.05$, respectively.

In this study, the integrated fertility scores were regarded as the integrated index of soil fertility. The regression analysis between maize yield and integrated fertility scores showed a significant linear positive correlation with maize yield ($p < 0.05$) (Table 6).

Table 6. Regression analysis of integrated fertility scores with maize yield.

Year	Stepwise Regression Equation	R^2	Significance Level
2021	Maize yield (t/ha) = 0.64x + 12.01	0.53	$p < 0.01$
2022	Maize yield (t/ha) = 0.98x + 12.35	0.25	$p < 0.05$

4. Discussion

4.1. Effects of Different Treatments on Soil Organic Matter and Its Components

Increasing SOM accumulation is the core content of soil fertility improvement, which can usually be achieved by exogenous organic compensation [13,35]. Numerous studies have confirmed that the addition of exogenous organic matter could significantly improve SOM [4,23,36]. Significantly, for soils with low SOM content (less than 10 g/kg), these organic fertilizer cultivation measures (straw returning, organic manure application, etc.) can rapidly replenish soil carbon, thus promoting soil carbon sequestration. This is probably because the poorer soil is in a state of "hunger" and has a high potential for carbon sequestration [37]. However, black soil is different. Before reclamation, the background SOM content of the black soil in Northeast China was generally high (about 75 g/kg), and after reclamation (about 50~100 years), the SOM content of the black soil sharply decreased (by 1/2 to 2/3), but the SOM content of the black soil was still much higher than that of barren soils in other areas [3,38,39]. Under this condition, the soil "hunger" state no longer exists. Perhaps because of this reason, straw-returning (SR and DS treatments) and organic manure (OM treatment) treatments did not increase SOM content significantly in this study (Figure 1). Some other research results also confirmed that exogenous straw returning and organic manure input are helpful to increase the SOM content of black soil, but carbon sequestration is slow [9,40]. Another reason might be that the C sequestration efficiency of straw is usually very low (about 7.7%), and it takes several years of continuous returning to the field to achieve a significant increase in SOM [41]. Therefore, it is quite difficult to achieve a large increase in SOM by the single addition of crop straw or organic manure in the short term.

Fortunately, the present study found that the natural humus material addition significantly increased SOM content. This might be due to the extremely high C/N ratio of natural humus material and its organic matter content being as high as 90% [19]. When natural humus material is put into soil, it can quickly replenish SOM content. Therefore, with the increase in the natural humus material application amount, the enhancement of SOM reached the level of significant difference (HWP treatment, Figure 1). In summary, straw returning (SR and DS treatments) and organic manure (OM treatments) can slightly improve SOM for a short time, but it is difficult to achieve a significant increase in SOM through a single implementation. Similar to previous reports, it might still need many years of multiple implementations to achieve a significant increase in soil SOM content. The addition of natural humus material can rapidly and greatly increase SOM content, which provides a reference way for the rapid improvement of SOM in a short term.

The total SOM is usually regarded as the result of the dynamic balance of soil organic substances [13]. The variation in the total SOM content is difficult to fully reveal the stability of SOM; thus, grouping SOM with different stabilities is beneficial to explain the stability of SOM [32]. The results of this study show that the contents of SOM components (LOM and AOM) and the total SOM content in different treatments had similar change trends (Figure 1). The highest values of both the LOM and AOM contents occurred in high added natural humus material treatment (HWP), followed by organic manure treatment (OM). This might be due to the fact that both natural humus material and organic manure are rich in humus components. Humic acids represent the residues of decomposed organic materials in soils, which contain aromatic substances with inert characteristics and relatively active alkoxy carbon substances [42]. Thus, the contents of LOM and AOM increased with the addition of natural humus material and organic fertilizer.

As a dissolved component of humus, microorganisms, and root exudates in soil, the DOM content can indirectly reflect the quality of SOM [34,43]. In this study, the OM and HWP treatments significantly enhanced the DOM content (Figure 2). Thus, it could be speculated that natural humus material and organic fertilizer additions might accelerate the turnover of soil nutrients (for example, the carbon metabolism of microbial communities), which in turn increases soil DOM accumulation, according to the results reported by Li et al. [34] and Wang et al. [43]. Furthermore, the addition of natural humus material also has potential advantages in enhancing the SOM stability. The stability of organic substances carried by natural humus material was much higher than that of natural SOM, and it has a more complex and stable molecular structure, such as a higher aromatic degree, a more compact structure, etc., but the organic matter within straw and organic fertilizer tends to be close to the soil active components [19]. The research results of Fu et al. [20] and Zheng et al. [19] also confirmed that the addition of natural humus material was more effective than organic manure or crop straw in preventing SOM degradation because the organic carbon molecular structure of natural humus material was far more stable than that in organic manure or crop straw. Based on the above analysis, we concluded that the application of natural humus material could not only rapidly increase the total amount of SOM, but also facilitate the accumulation of SOM stability components, which is of great significance for preventing SOM loss.

In conclusion, the SOM of black soil could be rapidly increased after the application of natural humus material and organic manure. The HWP treatment not only significantly increased the amount of SOM, but also improved SOM stability. Therefore, the application of natural humus material could be treated as an alternative method for the rapid enhancement of SOM in black soil, while straw returning and organic fertilizer could be used as supplementary fertilizer measures to mitigate SOM loss or maintain the existing SOM quantity.

4.2. Effects of Different Treatments on Soil-Integrated Fertility

In terms of the changes in the soil nitrogen, phosphorus, and potassium nutrient indexes, the HWP and OM treatments could improve the nitrogen and phosphorus contents of black soil to a certain extent (Figure 3). Some scholars revealed that organic amendments could promote nitrification, activate soil phosphorus, and then promote the accumulation of soil nitrogen and phosphorus [21,44–46]. Similarly, the contents of soil nitrogen and phosphorus increased obviously in HWP treatment. Because organic manure is rich in nitrogen, the application of organic manure could significantly improve soil nitrogen (Figure 3), which is consistent with the research results reported by Long et al. [47] and Ashraf et al. [9]. However, the TP content of OM treatment was slightly lower than that of other treatments, which was contrary to the past research results of some other scholars [48,49].

In addition, the alkaline substances from organic manure might alleviate the acidification of black soil according to the research results reported by some scholars [17,50,51]. However, the pH of OM treatment decreased significantly in this study (Figure 4). This might be due to the humification substances from organic manure releasing organic acids, which have a direct promoting effect on reducing the soil pH [52]. However, some other scholars proved that animal manure application could increase the risk of soil-exchangeable Na^+ accumulation in dry farms due to the high salt content of animal waste [17,53]. The significant increase in the EC value of OM treatment implies a significant increase in the amount of soil water-soluble salts, which also implies that the concentration of soil sodium salts might accumulate rapidly (Figure 5). Therefore, although the risk of sodium salt accumulation in OM treatment was not directly proven, it still required special attention to the risk of soil sodium salt accumulation due to the application of organic manure.

In this paper, the dimensionality reduction analysis of SOM, nitrogen, phosphorus, potassium, and other soil properties was carried out by using the principal component analysis method, and the key influencing factors of soil-integrated fertility were quantified. Finally, the fertility scores of soil-integrated fertilities were obtained (Tables 4 and 5). As

the most intuitive indicator for measuring soil fertility, crop yield had a significant positive linear regression relationship with the soil-integrated fertility scores (Table 6). It can be seen that the integrated fertility scores in this study reflect the level of black soil fertility; that is, a higher integrated fertility score indicates a higher soil fertility. Specifically, SOM and TP contributed the most to principal components both in 2021 and 2022, respectively (Tables 2 and 3). The results suggest that SOM and TP are the key nutritional indexes affecting the integrated fertility of black soil, which play a major role in the process of improving the integrated fertility.

Based on the above discussion, the addition of natural humus material had a great promotional effect on SOM, and the soil-integrated fertility increased significantly with the increase in the application amount of natural humus material. In addition, HWP treatment had the highest integrated fertility score. The results proved that the addition of natural humus material has a great effect on improving the fertility of black soil. In contrast, although organic fertilizer (OM treatment) and straw-returning (SR and DS treatments) applications had obviously higher soil-integrated fertility scores than CK, these fertilization measures are far inferior to natural humus material additions. Therefore, the addition of natural humus material is a better measure for the rapid accumulation of SOM and the rapid improvement of soil fertility than organic manure or straw returning.

5. Conclusions

The results of this study proved that natural humus material amendment could dramatically increase the content of SOM and its components through one application. The increased amount of SOM in HWP treatment was 9.36~9.41 g/kg, which was about 1.5 times of that of OM treatment (increased by 5.91~3.44 g/kg). In contrast, conventional soil fertility-improving practices (SR, DS, and OM treatments) had no significant enhancement in SOM in the short term. In addition, organic manure addition significantly increased soil EC values, which might increase the potential risk of soil sodium salt accumulation. The present study also proved that adding natural humus material had more advantages than organic manure and straw returning in improving soil fertility. Although the experimental design of unequal exogenous organic material addition might cause differences in the research results, the one-time application of natural humus material showed great positive effects on improving SOM and maize yield. Moreover, it is still of significance to further study the potential of natural humus material amendment in the fertility of black soil in future. Clarifying the rapid fertilization mechanism by applying natural humus material in future studies will also provide a reference for improving the quality of black soils and preventing the degradation of black cropland.

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