

Effect of different types of crop straw and its derivatives returning on soil nematode community

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ABSTRACT

Using straw derivatives to prevent plant nematodes disease is an effective and environmentally friendly technology. To investigate the effect of different types of straw derivatives (CK, no addition; A, rice straw ploughing; B, rice straw biochar; C, rice straw compost; H, biochar-based compost) on soil nematode community, a long-term field study was conducted under two cropping systems (maize [*Zea mays* L.] continuous cropping and maize-rice [*Oryza sativa* L.] rotation) in northeast China. Soil samples were collected at depth of 0-5, 5-10 and 10-20 cm at ripening stage, 2025. The results showed that bacterivores were the dominant genera in the C and H treatments. Treatment H had the highest abundance of fungivores and omnivore-carnivores and the lowest plant nematode disease incidences in comparison with CK. The average values of plant parasite index and channel index were 46.9% and 55.7% higher in compost involved input plots than in CK. Average 76.6% of microbial biomass C was accumulated in 0-5 cm. Biochar involved amendments showed slow release of available NPK. Overall, straw and its derivatives returning improved soil biological quality as evidenced by pushing the soil ecosystem entered into a more mature and less disturbed state.

Key words: Biochar, compost, maize, maize-rice rotation, soil nematode community, straw ploughing, straw returning.

INTRODUCTION

Agriculture waste, such as crop straw and livestock manure, is a major challenge worldwide. China is an agricultural country, which produces 3.8 billion tons of livestock manure and 900 million tons of crop straw each year (Yu et al., 2024). Approximately 520 million tons of crop straw was recycled to improve soil quality and increase crop yield through mechanization and composting each year in China (Sun et al., 2020). Each straw returning has its own shortcomings. For instance, mechanization showed the slowest decomposition rate in comparison with other forms, therefore, straw decomposition agents are usually needed. As for composting, the preparation process usually lasted 4-6 mo and large amount of repulsive odors would release during the process (Nguyen et al., 2022a).

To address these issues, high-temperature pyrolysis technology was used to produce straw biochar. Biochar is a kind of porous carbonaceous material with large Brunauer-Emmett-Teller surface area and strong adsorption ability (Zhong et al., 2025). At present, researchers found that mixing straw biochar into livestock manure for compost could not only increase mineralization rate of compost but also shorten the time for straw biodecomposition (Wang et al., 2021; Duan et al., 2021). The possible reason is biochar input promotes the growth and metabolism of microorganisms during composting (Situ et al., 2022).

Soil nematodes play an irreplaceable role in improving soil structure, increasing soil fertility and promoting organic matters cycling (Zhong and Zeng, 2019). A large number of studies found that soil nematode community was significantly affected by different types of straw returning. For instance, mixtures of crop straw and chemical

N fertilizer greatly increased the abundance of bacterivores and omnivore-carnivores (Wei et al., 2021). Input of straw biochar mixed with organic manure significantly increased the abundance of total nematodes (Huang et al., 2024), which meant the mixtures provided sufficient food for micro-feeding nematodes.

In summary, straw and its derivatives returning effectively improved soil physicochemical property was concerned by many researchers (Sun et al., 2020; Wei et al., 2021; Chamorro-Martínez et al., 2022), but few reports focused on preventing plant nematode disease caused by crop continuous cropping through input of straw biochar-based compost. In our study, the effects of straw and its derivatives returning (including crop straw ploughing, carbonization and composting) on soil nematode community composition and plant nematode disease incidence were investigated in a maize-rice rotation field, northeast China. This study would provide new technology to control plant nematode disease by straw returning.

MATERIALS AND METHODS

Site descriptions

The experiment was carried out on the Lishu Experimental Station (43°36'23.9" N, 124°05'19.9" E), Chinese Academy of Agriculture Sciences, since 2002. The region has a continental temperate monsoon climate with a mean annual temperature of 6.2 °C and a mean annual precipitation of 660 mm. The test soil is classified as Entisols, silty loam in USDA texture system with 33.0% sand, 40.1% silt and 26.9% clay. The soil has initial properties of 13.6 g kg⁻¹ total organic C, 1.27 g kg⁻¹ total N, 0.79 g kg⁻¹ total P, 1.21 g kg⁻¹ total K and pH 6.76.

The experiment was a split-plot design with four replicates under conventional tillage. Cropping system (maize [*Zea mays* L.] monocropping, M; maize-rice [*Oryza sativa* L.] rotation, R; 4-yr of maize followed by 4-yr of rice) was the main plot and straw returning was the sub-plot. The field experiment was divided into two plots (20 × 20 m² each) under a completely randomized block design. Straw returning included no addition (CK), rice straw ploughing (A), rice straw biochar (B), composted rice straw (C), biochar-based compost (H).

Biochar (< 0.5 mm) was prepared from rice straw under oxygen-limited furnace at 600 °C for 5 h, with 3.07% moisture, pH 8.64, 252.2 m² g⁻¹ specific surface area, 0.767 cm³ g⁻¹ pore volume, 69.6% total organic C, 2.57% total N, 1.44% total P, 4.49% total K. Compost aerobically composted from rice straw and pig manure, contained 50.5% moisture, pH 7.84, 48.1% total organic C, 3.36% total N, 2.25% total P, 1.39% total K on dry weight. Biochar-based compost prepared by rice straw biochar mixed into the pig manure at the beginning of the composting process, contained 46.9% moisture, pH 7.33, 54.3% total organic C, 3.97% total N, 2.86% total P, 1.77% total K on dry weight. The mass ratio of pig manure and biochar in both types of compost was 7:3 (on dry weight). Compost and biochar were basally applied before planting to a depth of 0-30 cm. Rice straw (< 2 mm) was ploughed into 0-30 cm soil depth after harvest, contained 32.3% moisture, pH of 6.67, 38.9% total organic C, 1.84% total N, 0.986% total P, 3.12% total K on dry weight. Additive amount of each amendment was 50 t ha⁻¹.

Soil sampling

Soil samples were collected at depth of 0-5, 5-10 and 10-20 cm using a soil corer (2.5 cm diameter) at the ripening stage (23 September 2025). Each soil sample pooled from five soil cores was stored in individual plastic bags, and transferred to a 4 °C icebox.

A sample of 100 g soil (fresh weight) was used for nematode extraction. Samples were elutriated and sieved (mesh size 250 and 38 μm) with water and the suspensions were then extracted using a modified cotton-wool filter method (Townshend, 1963) for 48 h. The collected nematodes were heat-killed (60 °C) and fixed with 4% triethanolamine formaldehyde (TAF).

Each nematode suspension was counted using a dissecting microscope. An average of 150 nematodes (100 nematodes at minimum) per sample were identified using an inverted compound microscope at 400X to 1000X to genus or family level. The abundance of nematodes was expressed per 100 g dry weight soil. Nematodes were assigned to feeding groups (Yeates et al., 1993) and to colonizer-persister (c-p) classes (Bongers and Bongers, 1998).

Soil moisture (SM) was determined gravimetrically by drying samples at 105 °C for 48 h. Soil total organic C (TOC) was measured by dry combustion, using a solid sample combustion module (SSM-5000A, Shimadzu, Kyoto, Japan). Soil total N (TN) was determined by Kjeldahl digestion. Soil available N (AN) was analyzed by Continuous Flow Analytical System (AutoAnalyzer 3, SEAL Analytical, Norderstedt, Germany). Soil available P (AP) and soil available K (AK) were analyzed by spectrophotometer (7200, Unico Instrument, Shanghai, China) and flame photometer (FP 640, INESA Analytical Instrument, Shanghai, China), respectively (Lu, 2000). Soil microbial biomass C (MBC) and N (MBN) were measured using the chloroform fumigation-extraction method (Vance et al., 1987).

Statistical analysis

Diversity of microfauna was assessed by Shannon-Weaver diversity (H') (Shannon, 1948) and species richness (SR) (Neher et al., 1995). Maturity index (MI) and plant parasite index (PPI) were calculated according to Yeates and Bongers (1999). The structure index (SI), enrichment index (EI), basal index (BI) and channel index (CI) were calculated according to Ferris et al. (2001). Plant pathogenic nematode disease incidence was calculated as percentage of infected plants to total plants.

Microfauna data were $\ln(x+1)$ transformed prior to statistical analysis. Data were analyzed by SPSS statistical software (IBM, Armonk, New York, USA). Means were compared between treatments and soil depth by least significant difference (LSD). Difference at $p < 0.05$ level was considered significant.

RESULTS

Soil property

Treatment and soil depth effects were significant on the concentration of available N, microbial biomass C and microbial biomass N ($P < 0.01$, Table 1). Biochar-based compost plots showed the highest concentration of soil moisture, total N and microbial biomass C followed by compost input plots. Although total organic C, available P and available K showed nonsignificant difference among straw derivatives input plot, the concentrations were much higher than those in CK (Figure 1).

The concentration of microbial biomass C and N in rotation plots increased 39.8% and 50.2% in comparison with monocropping plots. The concentration of available P was mainly accumulated in 0-5 cm under biochar involved plots, and nonsignificant differences were found between 5-10 cm and 10-20 cm (Figure 1). However, the concentration of available N and K decreased sharply with the increase of soil depth under the treatments without biochar amendment.

Table 1. Effects of straw returning, cropping type, soil depth and interaction among these variables on soil nematode and physicochemical properties. TNEMA: Total nematodes; BF: bacterivores; FF: fungivores; OP: omnivore-predators; PP: plant parasites; H' : Shannon-Weaver diversity; SR: species richness; MI: maturity index; PPI: plant parasite index; BI: basal index; CI: channel index; EI: enrichment index; SI: structure index; SM: soil moisture; TOC: total organic C; TN: total N; AN: available N; MBC: microbial biomass C; MBN: microbial biomass N; ^{ns}: nonsignificant effect.

ANOVA	Soil depth						
	Straw returning (S) <i>P</i> value	Rotation (R) <i>P</i> value	(D) <i>P</i> value	S×R <i>P</i> value	S×D <i>P</i> value	R×D <i>P</i> value	S×R×D <i>P</i> value
TNEMA	0.037	< 0.01	0.011	< 0.01	0.047	ns	ns
BF	< 0.01	ns	< 0.01	< 0.01	ns	ns	< 0.01
FF	< 0.01	ns	< 0.01	ns	< 0.01	< 0.01	ns
OP	ns	0.036	< 0.01	< 0.01	< 0.01	< 0.01	ns
PP	< 0.01	< 0.01	0.038	< 0.01	ns	ns	ns
H'	0.019	< 0.01	< 0.01	0.041	ns	ns	< 0.01
SR	0.023	< 0.01	< 0.01	ns	< 0.01	< 0.01	ns
MI	< 0.01	ns	< 0.01	< 0.01	0.040	< 0.01	ns
PPI	< 0.01	0.026	< 0.01	< 0.01	< 0.01	ns	ns
BI	< 0.01	ns	0.013	ns	< 0.01	< 0.01	ns
CI	< 0.01	0.028	ns	< 0.01	< 0.01	< 0.01	0.015
EI	< 0.01	ns	< 0.01	< 0.01	ns	ns	< 0.01
SI	< 0.01	ns	< 0.01	0.044	ns	< 0.01	ns
SM	ns	< 0.01	< 0.01	ns	< 0.01	< 0.01	ns
TOC	ns	< 0.01	< 0.01	ns	ns	0.030	< 0.01
TN	< 0.01	ns	ns	< 0.01	< 0.01	< 0.01	ns
AN	< 0.01	0.019	< 0.01	0.031	ns	< 0.01	ns
AP	ns	ns	< 0.01	ns	ns	ns	0.035
AK	ns	0.020	ns	ns	< 0.01	< 0.01	ns
MBC	0.017	< 0.01	< 0.01	< 0.01	ns	< 0.01	ns
MBN	0.039	< 0.01	0.010	< 0.01	ns	ns	0.029

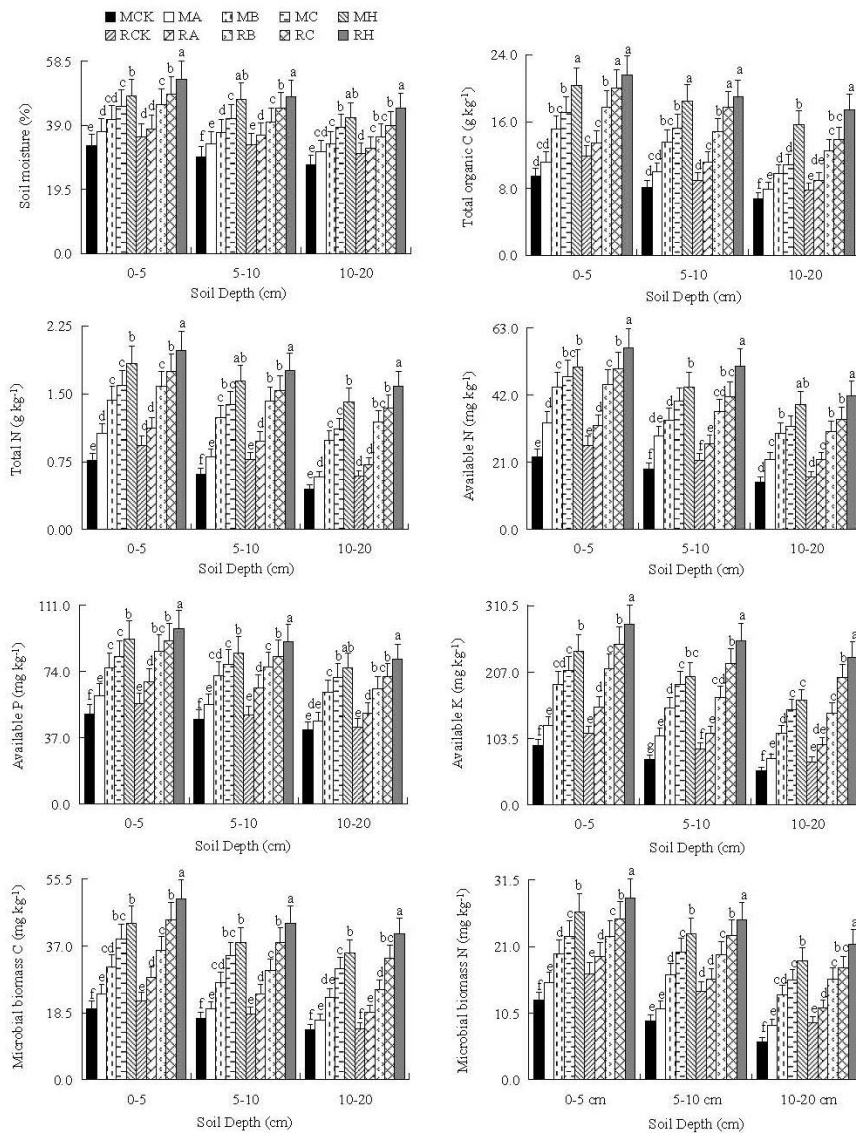


Figure 1. Soil properties under straw returning at each soil depth. M: Maize monocropping; R: maize-rice rotation; CK: no addition; A: rice straw ploughing; B: rice straw biochar; C: rice straw compost; H: biochar-based compost. Error bars mean standard error. Different lowercase letters above the mean values mean significant difference ($P < 0.05$).

Nematode composition

Significant treatment and soil depth effects were observed on the abundance of total nematodes ($P < 0.05$, Table 2). The average abundance of total nematode in 0-5 cm and 5-10 cm was 39.7% and 25.8% higher than that in 10-20 cm (Figure 2). Bacterivores and fungivores enriched in 0-5 cm, while omnivore-carnivores were always collected in 10-20 cm.

Forty-four genera belonging to 27 family were found in all the treatments and bacterivores were the dominant genera in all straw derivatives input plots and H treatment showed the highest abundance and species. Plant parasites such as *Hirschmanniella*, *Pratylenchus* and *Criconea* were the dominant genera in straw ploughing plots and CK (Table 2).

Rotation significantly increased the abundant of omnivore-carnivores, bacterivores and fungivores with c-p 3 and c-p 4, while bacterivores and fungivores with c-p 2 were the dominant genera in monocropping combined with compost input plots (Table 2).

Biochar-based compost plots exhibited the lowest plant nematode disease incidence (4.89%), followed by compost input (6.65%), and straw ploughing showed the worst prevention (30.5%). Rotation decreased the incidence by 24.9% but the effectiveness was far less than straw derivative input.

Table 2. Average contribution (%) of different nematode genera to total nematodes in different cropping types under four straw returning systems. CK: No addition; A: rice straw ploughing; B: rice straw biochar; C: rice straw compost; H: biochar-based compost. ^aFunctional guilds of soil nematodes characterized by feeding habits and life-history characters: Bacterivores (Ba_x), fungivores (Fu_x), carnivores (Ca_x), omnivores (Om_x), herbivores (PP_x); numbers (x) following the functional guilds indicate the colonizer-persister (c-p) values (Bongers and Bongers, 1998; Ferris et al., 2001). **Dominant genus, average contribution (%) of different nematode genera to total nematodes is more than 10%; *Subdominant genus, average contribution (%) is over 5%; ns: nonsignificant.

Genus	Mono-cropping					Rotation					Guilds ^a	Effect		
	CK	A	B	C	H	CK	A	B	C	H		Straw Incorporation	Soil depth	Cropping type
	%					%								
Bacterivores	26.97	30.21	34.79	39.14	42.29	28.66	32.06	37.11	40.31	42.89				
<i>Mesorhabditis</i>	3.22	3.07	1.63	0.53	0.67	4.36	2.22	1.14	2.12	0.56	Ba ₁	ns	ns	< 0.01
<i>Pelodera</i>	0.87	1.43	1.31	1.32	0.78	1.47	3.21	2.22	1.22	0.65	Ba ₁	ns	< 0.01	< 0.01
<i>Panagrolaimus</i> *	8.77	7.44	2.13	0.45	3.16	7.63	6.23	0.62	2.18	0.49	Ba ₁	< 0.01	< 0.01	ns
<i>Diplogasteritus</i> *	5.54	5.97	0.76	0.85	0.38	6.25	6.45	1.78	0.63	1.31	Ba ₁	ns	0.017	< 0.01
<i>Eucephalobus</i>	2.16	0.83	3.24	1.98	2.15	0.44	0.00	3.65	1.49	1.98	Ba ₂	0.014	< 0.01	0.031
<i>Heterocephalobus</i> *	0.27	1.78	0.66	5.64	2.03	0.00	0.99	4.34	6.22	3.78	Ba ₂	ns	< 0.01	< 0.01
<i>Acrobeloides</i> *	0.95	1.58	0.85	2.11	1.18	1.12	1.43	5.87	2.42	4.72	Ba ₂	ns	ns	0.022
<i>Cervidellus</i>	0.00	0.00	3.37	3.24	0.71	0.00	4.21	0.33	1.89	1.24	Ba ₂	0.048	ns	ns
<i>Plectus</i>	1.01	0.73	0.00	2.26	2.27	0.00	1.77	2.15	3.84	3.75	Ba ₂	< 0.01	ns	ns
<i>Wilsonema</i>	0.00	2.32	2.45	0.55	4.23	0.98	0.00	0.00	2.29	3.15	Ba ₂	< 0.01	< 0.01	ns
<i>Chronogaster</i>	0.79	3.71	4.18	1.04	1.32	1.35	0.68	2.56	1.38	1.75	Ba ₂	ns	< 0.01	0.043
<i>Leptolaimus</i>	1.13	0.00	0.35	0.97	2.96	3.65	2.55	0.30	1.74	0.73	Ba ₂	ns	ns	0.015
<i>Rhabdolaimus</i>	0.00	0.19	2.04	1.33	1.87	0.00	1.74	0.28	0.66	0.33	Ba ₃	0.016	< 0.01	ns
<i>Aulolaimus</i>	0.72	0.00	2.39	1.68	0.68	0.00	0.00	1.34	0.00	0.61	Ba ₃	< 0.01	< 0.01	ns
<i>Pseudoaulolaimus</i> *	0.00	0.14	1.56	2.34	5.57	0.79	0.21	2.43	2.86	6.23	Ba ₃	0.033	ns	ns
<i>Prismatolaimus</i> *	0.22	0.59	4.39	7.48	5.42	0.62	0.00	3.77	3.74	4.44	Ba ₃	< 0.01	ns	< 0.01
<i>Alaimus</i> *	1.32	0.43	3.48	5.37	6.91	0.00	0.37	4.33	5.63	7.17	Ba ₄	< 0.01	0.034	< 0.01
Fungivores	9.92	13.87	15.96	18.91	20.48	11.76	14.94	17.07	19.67	21.02				
<i>Ditylenchus</i> *	5.52	3.81	0.54	0.65	0.72	3.97	0.88	0.68	0.91	0.42	Fu ₂	ns	ns	< 0.01
<i>Aphelenchus</i> *	2.83	2.09	2.19	5.59	3.44	0.79	5.24	3.54	2.68	0.98	Fu ₂	ns	0.032	ns
<i>Aphelenchoides</i> *	1.14	6.03	1.79	6.22	2.67	5.88	5.41	2.73	1.89	6.87	Fu ₂	ns	< 0.01	< 0.01
<i>Dorylaimoides</i> *	0.43	1.94	7.68	2.98	5.88	0.0	1.47	6.44	8.43	5.54	Fu ₄	< 0.01	0.048	< 0.01
<i>Tylencholaimus</i> *	0.00	0.00	3.76	3.47	7.77	1.12	1.94	3.68	5.76	7.21	Fu ₄	0.019	ns	0.043
Omnivore-carnivores	21.91	25.20	29.03	31.49	33.32	23.15	27.03	30.45	32.70	33.82				
<i>Tobrilus</i> *	5.87	6.99	0.12	2.48	0.57	2.01	1.25	0.39	1.87	1.43	Ca ₃	ns	< 0.01	0.026
<i>Prionchulus</i> *	6.33	5.44	0.84	3.34	1.65	1.13	2.96	1.85	0.49	2.47	Ca ₄	0.022	< 0.01	0.043
<i>Thonus</i>	1.08	0.79	0.49	0.39	3.43	0.88	1.87	0.89	2.14	1.04	Om ₄	ns	< 0.01	ns
<i>Eudorylaimus</i> *	0.99	0.88	5.23	3.14	5.79	1.29	1.32	4.23	3.21	7.76	Om ₄	ns	ns	ns
<i>Epidorylaimus</i>	2.56	1.53	2.89	2.81	3.57	2.61	1.25	2.89	1.24	2.10	Om ₄	ns	ns	ns
<i>Dorydorella</i>	0.00	0.15	0.44	0.00	0.74	0.40	0.24	0.44	1.82	4.03	Om ₄	ns	ns	0.039
<i>Microdorylaimus</i> *	1.21	1.37	0.00	3.11	5.66	1.49	5.65	0.00	6.98	2.97	Om ₄	0.033	ns	ns
<i>Kochinema</i>	0.00	2.66	1.36	1.65	1.18	0.00	1.97	1.36	2.22	1.77	Om ₄	0.028	< 0.01	< 0.01
<i>Aporcelaimellus</i> **	0.00	0.00	11.40	8.87	5.05	1.79	1.44	5.34	8.76	5.43	Om ₅	< 0.01	0.044	< 0.01
<i>Aporcelaimus</i>	0.66	0.63	1.85	1.95	2.63	0.00	0.54	7.65	1.67	3.02	Om ₅	ns	ns	ns
<i>Prodorylaimus</i> *	0.00	3.29	0.74	1.74	1.16	6.21	6.63	0.74	1.80	1.11	Ca ₅	0.012	< 0.01	ns
<i>Mesodorylaimus</i> *	3.21	1.47	3.67	2.01	1.89	5.34	1.91	4.67	0.50	0.69	Ca ₅	< 0.01	ns	0.030
Plant parasites	41.20	30.20	20.20	10.40	3.91	36.43	25.97	15.37	7.32	2.27				
<i>Tylenchus</i> *	2.39	2.44	5.22	3.83	0.78	1.69	3.48	1.75	0.60	0.51	PP ₂	0.019	ns	< 0.01
<i>Filenchus</i> *	5.89	3.31	0.99	1.32	0.25	5.43	3.14	0.85	1.07	0.62	PP ₂	ns	< 0.01	ns
<i>Psilenchus</i>	0.51	3.97	0.00	0.49	1.23	2.09	1.73	0.44	1.52	0.38	PP ₂	< 0.01	0.035	ns
<i>Hirschmanniella</i> *	6.39	4.22	2.13	3.64	0.46	5.05	3.97	1.82	1.14	0.41	PP ₃	ns	< 0.01	0.038
<i>Pratylenchus</i> **	10.40	6.04	3.12	0.50	0.00	8.66	6.11	0.00	0.17	0.00	PP ₃	0.036	0.027	0.020
<i>Meloidogyne</i>	3.89	2.13	0.00	0.00	0.00	2.76	0.61	3.62	0.00	0.00	PP ₃	ns	ns	ns
<i>Criconema</i> *	8.57	5.44	0.17	0.43	0.54	7.96	5.02	2.30	0.18	0.23	PP ₃	0.044	ns	ns
<i>Paratrichodorus</i> *	0.00	2.39	6.58	0.00	0.00	0.00	1.22	2.17	1.78	0.12	PP ₄	ns	< 0.01	< 0.01
<i>Dorylaimellus</i>	2.67	0.00	2.01	0.00	0.65	1.05	0.00	2.42	0.00	0.00	PP ₅	< 0.01	ns	ns
<i>Oxydirus</i>	0.49	0.78	0.00	0.25	0.00	1.74	0.69	0.00	0.86	0.00	PP ₅	ns	ns	0.018

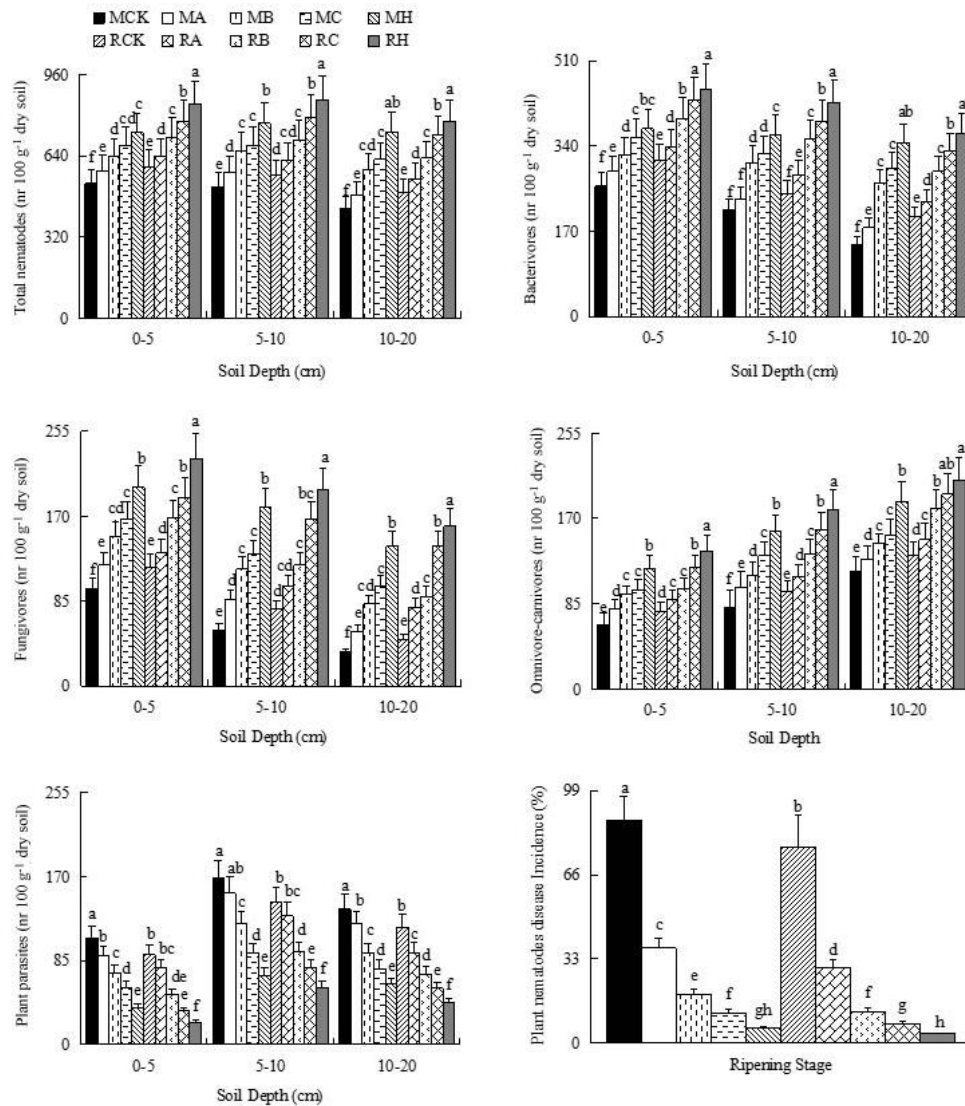


Figure 2. The abundance of soil nematodes and plant nematodes disease incidence under straw returning at each soil depth. M: Maize monocropping; R: maize-rice rotation; CK: no addition; A: rice straw ploughing; B: rice straw biochar; C: rice straw compost; H: biochar-based compost.

Community indicators

For soil depth, H¹, SR and EI showed the highest values in 0-5 cm. Maturity index (MI) and SI showed the highest values in 10-20 cm (Figure 3). Plant parasite index (PPI) showed the highest values in 5-10 cm. For cropping types, H¹ and SR were significantly higher in rotation plots than those in monocropping plots, while BI and SI showed nonsignificant difference between cropping types.

Biochar-based compost input plot showed the highest values of SR, MI, SI and EI, followed by compost input plot in comparison with CK (Figure 3). The values of PPI, BI and CI in straw derivatives input plots were significantly lower than those in straw ploughing plots and CK (Figure 3).

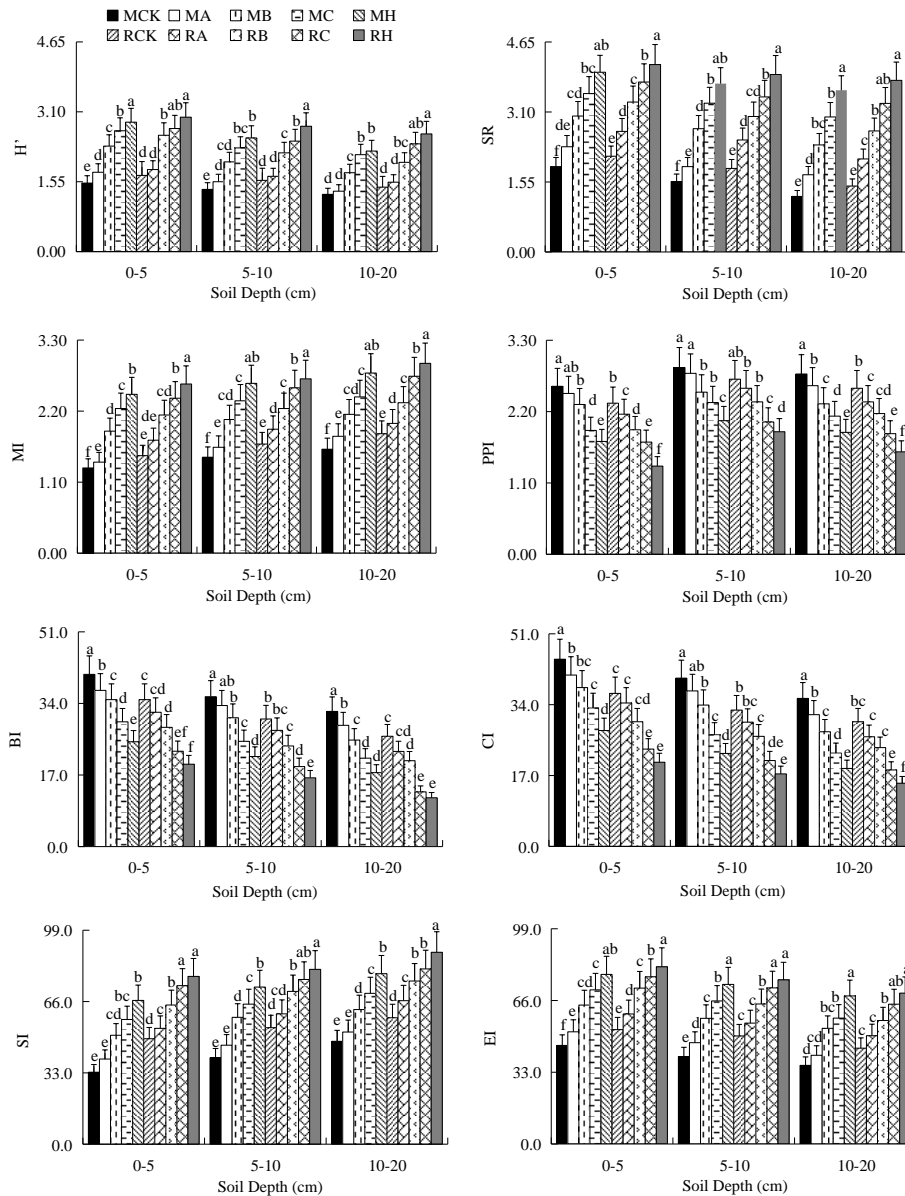


Figure 3. Nematode ecological indices under straw returning at each soil depth. M: Maize monocropping; R: maize-rice rotation; CK: no addition; A: rice straw ploughing; B: rice straw biochar; C: rice straw compost; H: biochar-based compost; H': Shannon-Weaver diversity; SR: species richness; MI: maturity index; PPI: plant parasite index; BI: basal index; CI: channel index; EI: enrichment index; SI: structure index; A: straw ploughing; B: straw biochar; C: straw compost; H: biochar-based compost.

DISCUSSION

Effect of straw returning on plant nematode disease control

In the study, the average incidence in biochar-based compost input plots was 413.6% lower than that in control (CK), which was consistent with Debode et al. (2020). They reported that oak wood biochar-based compost was more effective than pesticides on plant nematode disease prevention. The mechanisms were as follows: (1) Biochar adsorbed toxic emissions during composting, which were harmful to free-living nematode (Ebrahimi et al., 2021); (2) biochar prolonged the high-temperature period and improved organic matter degradation (Chen and Liang, 2025); (3) biochar accumulated large amount of nutrients around roots which promoted the growth of hosts and beneficial microorganisms; and prevented the infection of plant parasites (Cao et al., 2018).

Straw ploughing had the worst control effect with the incidence of 33.2%. Previous studies found that wheat straw ploughing could not decrease the abundance of *Meloidogyne* spp. (Sarker et al., 2023). The reason was that the plant pathogenic nematodes such as *Pratylenchus*, *Meloidogyne* and *Criconeema* showed strong ability of viability, reproduction, hatching and infectivity (Oka, 2022). Their eggs could rest for many years after entering into the soils with straw ploughing.

Effect of straw returning on nematode community

In the study, biochar-based compost (H) treatment had more bacterivores and fungivores with high colonizer-persister (c-p) values than other treatments and composted rice straw (C) and H treatments had more omnivores than CK. Liu et al. (2020) found similar results and explained that biochar added at composting process enhanced compost quality such as suitable moisture, porosity, pH and C/N, and soil total organic C, total N and available NPK in 10-20 cm were greatly increased after application. In the study, straw ploughing plots had higher abundance of bacterivores and fungivores with c-p 2, which would tolerate nutrients shortage, in comparison with CK. Other researchers found similar results (Silva et al., 2022), indicating that aliphatic substrates, carbohydrates and polysaccharides contained in rice straw were difficult to biodegrade during straw ploughing in comparison with composting process.

In the study, most of the bacterivores and fungivores were distributed in 0-5 cm, where high abundance of microorganisms was collected, for the input of large amount of compost, biochar and crop residues. Herren et al. (2020) found similar results. In the study, average around two third of plant parasites were distributed in 5-10 cm, which was generally limited to the depth of root penetration of the hosts. However, carnivores and omnivores had to move downward to 10-20 cm, which was consistent with Hu et al. (2020). The reason was that biochar-based compost induced hosts releasing large amount of allelopathic substances such as gibberellin, which inhibited the activity of omnivores, as well as carnivores (Sun et al., 2020).

Effect of straw returning on nematode ecological indicators

In the study, the highest Shannon-Weaver diversity (H'), species richness (SR) and enrichment index (EI) were found in 0-10 cm at all organic amendment plots, which was consisted with the highest concentration of soil moisture, total N and total organic C at the same soil depth. Pan et al. (2022) also found that available nutrients usually accumulated at soil surface layer which provided sufficient food sources for free-living nematodes.

In the study, the highest values of maturity index (MI) and structure index (SI) were found in 10-20 cm. The result was particularly noticeable at biochar involved plots, which was in agreement with the results of Cao et al. (2018). The reason was because biochar input reduced the disturbances caused by harmful substances such as heavy metals, antibiotics and pesticides.

In the study, plant parasite index (PPI) and basal index (BI) significantly decreased in compost involved plots, which was consistent with Nguyen et al. (2022b). The result was because the endogenous microorganisms in the compost significantly suppressed the behavior of plant parasites. In the study, channel index (CI) in rotation treatments at 0-20 cm were significantly lower than those in mono-cropping treatments, attributing to the increased ratio of bacterial feeder Ba2, to fungal feeder Fu2 (Table 1). Fang et al. (2025) also found that decomposition channel in a peanut-cotton rotation field was dominated by bacterivores.

CONCLUSIONS

In conclusion, biochar involved treatments greatly increased the concentration of total organic C and available nutrients. Biochar-based compost input increased the diversity and abundance of free-living nematodes, and built up an undisturbed and structured soil food web. Straw and its derivatives returning effectively decreased the abundance of plant parasites and improved soil quality and ecological environment in northeast China.

Author contributions

Conceptualization: S.Z. Methodology: T.S. Software: Y.L. Validation: Y.L. Formal analysis: Y.Q. Investigation: X.B. Resources: X.B. Data curation: T.S., Y.L. Writing-original draft: S.Z., T.S., Y.L. Writing-review & editing: S.Z., Y.Q. Supervision: Y.Q. Project administration: S.Z. Funding acquisition: S.Z. All co-authors reviewed the final version and approved the manuscript before submission.

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