https://doi.org/10.5194/egusphere-2025-5686
Preprint. Discussion started: 12 December 2025

Magnetic separation reveals overestimation of soil organic matter due to undecomposed particulate residues

Yuhan Xia[a], Sen Dou[a,*], Song Guan[a,*], Dilimulati Yalihong[a]

[a]Key laboratory of Soil Resource Sustainable Utilization for Commodity Grain Bases of Jilin Province, College of Resource and Environmental Science, Jilin Agricultural University, Changchun 130118, China

18543718988@163.com (Y. Xia); 17843098635@163.com (D. Yalihong).

*Corresponding author.

Tel:13504486204, E-mail: dousen1959@126.com (S. Dou); Tel:13504467990, E-mail: guansong8888@163.com (S. Guan).

https://doi.org/10.5194/egusphere-2025-5686
Preprint. Discussion started: 12 December 2025

Abstract

Soil organic matter (SOM) is a complex mixture of organic compounds derived from the decomposition of plant and animal residues. Only after undergoing microbial transformation and forming stable associations with minerals can it be considered "true" SOM, rather than a simple mechanical accumulation of carbon-containing substances. According to current understanding, particulate organic matter (POM) comprises both undecomposed and partially decomposed organic residues. Of these, the undecomposed fraction does not qualify as SOM in the strict sense. However, conventional analytical methods cannot fully distinguish fine particulate residues from soil matrices, leading to an overestimation of POM-derived carbon content. The extent and persistence of this "false increase" in SOM due to "disguised" POM remains poorly understood. In this study, straw and biochar were magnetized via chemical co-precipitation and applied to soils. The incompletely decomposed magnetized residues in the soil were separated using magnetic separation at various time points, enabling more accurate tracking of SOM dynamics. Five treatments were established: blank control (CK), untreated straw (CS), untreated biochar with carbon input equivalent to untreated straw (Bc), magnetized straw with carbon input equivalent to untreated straw (MCS), and magnetized biochar with carbon input equal to untreated straw (MBc). The results showed that after the application of organic materials into the soil, the recovery rate of magnetized straw residues declined continuously, reaching 54.55% after 360 d, whereas biochar remained largely stable at 92.48%. In CS and Bc treatments, the organic carbon content of POM fractions and their proportion in the total SOM were consistently higher than in CK, particularly during early incubation. However, this was attributable to overestimation from incompletely decomposed

residues. In contrast, MCS-D and MBc-D treatments (after magnetic residue removal) showed minimal deviation from CK, confirming the contribution of incomplete decomposition to SOM overestimation. On day 30, the apparent increase in the particulate organic carbon (*POC*) content reached 63.48% for CS and 58.99% for Bc. Over time, the overestimation in the CS treatment declined to 15.34% by day 360, whereas the overestimation in the Bc treatment remained largely unchanged, with a 53.71% increase persisting. These findings highlight the potential for SOM overestimation when POM fractions are fully included without accounting for undecomposed inputs, particularly the long-term persistence of recalcitrant organic materials, which may introduce systematic bias in global SOM quantification.

Keywords: Particulate Organic Matter (POM); Soil Organic Matter (SOM); Magnetic Materials; Straw; Biochar

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1. Introduction

Soil organic matter (SOM) is a complex assemblage of organic compounds formed by the decomposition and transformation of plant and animal residues, with the greatest binding to minerals. It originates from partial microbial decomposition of plant detritus (Angst et al., 2021; Cotrufo et al., 2013; Dou et al., 2020; Vendig et al., 2023). The core of SOM lies in organic constituents with dynamic transformation characteristics that supply nutrients to soil, sustain microbial activity, and influence soil structure (Feng et al., 2025), rather than in the accumulation of carbon-containing substances. Distinct SOM components exhibit different turnover rates and stabilization mechanisms (Sokol et al., 2022; Von Lützow et al., 2007). Cambardella and Elliott (1992) proposed a physical fractionation method based on particle size to extract particulate organic matter (POM) ranging from 2 mm to 53 μm. Conceptual models for SOM formation and stabilization have been developed based on these fractions (Christensen, 1992; Cotrufo and Lavallee, 2022; Guo et al., 2022; Lavallee et al., 2020; Rocci et al., 2021; Witzgall et al., 2021).

In recent years, soil management and improvement measures have primarily aimed to increase organic material inputs and promote microbial utilization to form SOM (Cotrufo et al., 2013; Castellano et al., 2015). However, when application rates exceed microbial decomposition capacity, substantial amounts of undecomposed organic material can accumulate in POM over a certain period (Bhattacharyya et al., 2011; Brown et al., 2014; Stewart et al., 2012), leading to sharp short-term increases in POM organic carbon content (Hua et al., 2022; Liang et al., 2016; Mitchell et al., 2018). This increase is “spurious”, as POM remains susceptible to decomposition and transformation even under the physical

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protection of soil (Connell et al., 2025), and such short-term increases are unstable (Janzen, 2015; Powlson et al., 2014). Currently, an accurate assessment of the proportion and duration of this "spurious increase" in POM mass and organic carbon content at various times following organic material application is still lacking.

In routine experiments, methods such as heavy liquid separation, sieving, and electrostatic attraction can isolate some undecomposed organic materials. However, they are less effective for highly fragmented materials such as biochar, limiting evaluation of SOM transformation processes. Therefore, new approaches for efficient separation of undecomposed residues are required. Magnetized materials (e.g., iron-based materials such as nano-zero-valent iron and iron sulfides) can be rapidly separated from soil under an external magnetic field, enabling the efficient recovery of target substances (Li et al., 2024; Rana et al., 2025; Zhang et al., 2025). Although biochar modified with magnetized materials has been widely studied, most research has focused on heavy metal or pollutant adsorption, with no application in SOM transformation. Among magnetized material preparation methods, the chemical coprecipitation method has been widely used because of its operational simplicity, high efficiency, and ease of impurity removal (Zhou et al., 2019). It offers excellent biocompatibility, stability, and recyclability (Baragaño et al., 2020; Duan et al., 2022), which facilitate the combined application of organic materials in soil.

In this study, a chemical coprecipitation method was used to composite straw (CS) and straw biochar (Bc) into magnetized materials. At different incubation stages, undecomposed magnetized organic residues were separated using an external magnetic field to eliminate their interference in SOM determination. This approach allowed the accurate achievement of

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three objectives: (i) to quantify and characterize the incompletely decomposed residues at different times after organic material application; (ii) to determine the existence, proportion, and duration of a "spurious increase" in POM organic carbon; and (iii) to assess the proportion of organic residues ultimately transformed into stable SOM. The results provide critical support for precise evaluation of POM organic carbon content and elucidation of the mechanisms by which organic materials are transformed into stable SOM.

2. Materials and Methods

2.1. Experimental materials

The test soil was collected from the experimental station of Jilin Agricultural University, located in the semi-humid region of Northeast China (43°48′43.57″N, 125°23′38.50″E). The region has a temperate semi-humid climate, with an annual mean temperature of 4.6°C and average annual precipitation ranging from 600 to 700 mm. The soil is classified as Black Soil under the suborder of semi-moist temperature semi-eluvial soil in the Chinese soil classification system, which is equivalent to Argiudolls in the USDA soil taxonomy. In September 2023, 100 soil samples were randomly collected from the 0–20 cm layer using a soil auger and combined to form a composite sample. After sampling, visible organic residues were manually removed. The field-moist soil was air-dried and sieved through a 2 mm mesh for subsequent incubation. The basic properties of the soil were as follows: soil organic matter, 22.76 g kg^{-1}; total nitrogen, 1.28 g kg^{-1}; available nitrogen, 132.21 mg kg^{-1}; available phosphorus, 18.52 mg kg^{-1}; and available potassium, 99.32 mg kg^{-1}.

The corn stover (CS) used in the experiment was obtained from the Experimental

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Station of the Jilin Agricultural University, Jilin Province, China (Changchun, China). The entire CS was rinsed with deionized water to remove surface ash and soil, dried in an oven for 24 h, ground using a grinder, and sieved through a 20-mesh sieve for later use.

The sieved straw powder (passing 20 mesh) was placed in a tubular furnace and pyrolyzed at 500°C for 2 h under a nitrogen atmosphere at a heating rate of 5°C min^{-1}. After cooling to room temperature, the resulting black solid was collected as straw biochar (Bc) for further use.

The magnetized straw (MCS) and magnetized biochar (MBc) were prepared using the chemical coprecipitation method (Zhou et al., 2019) as follows: 2.5 g of $FeCl_3 \cdot 6H_2O$ and 1.5 g of $FeSO_4 \cdot 7H_2O$ (Fe^{3+}:Fe^{2+} molar ratio of 2:1) were weighed into a beaker. Subsequently, 2.0 g of dried CS or Bc was introduced to 100 mL of ultrapure water. The mixture was thoroughly stirred at room temperature for 30 s using a magnetic stirrer. An excess of ammonia solution ($NH_3 \cdot H_2O$) was subsequently added to adjust the pH to 10. After the reaction, the magnetic materials in the suspension were separated from the liquid phase using an external magnet. The magnetized samples were collected, dried in a vacuum oven at 60°C, weighed, and designated as magnetized straw (MCS) and magnetized biochar (MBc).

2.2. Experimental Design

Prior to the incubation experiment, the collected soil was pretreated by thorough mixing and sieving through a 2 mm mesh. Fine roots and other visible plant residues were carefully removed, and all iron-containing particles were extracted using a magnetic rod to minimize potential experimental interference. The study included five treatments: (1) control (CK): no

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organic amendment; (2) straw treatment (CS): non-magnetized straw; (3) biochar treatment (Bc): non-magnetized biochar with carbon content equivalent to CS; (4) magnetized straw treatment (MCS): magnetized straw at the same carbon input as CS; and (5) magnetized biochar treatment (MBc): magnetized biochar with carbon equivalent to CS.

For each treatment, the respective materials (CS, Bc, MCS, and MBc) were thoroughly mixed with soil. Specifically, 400 g of soil was placed in PVC containers, and amendments were applied based on a full straw return rate of 11 t ha^{-1}. Accordingly, 1.95 g of straw was added to the CS treatment, while 1.16 g of biochar was applied to the Bc treatment to match the carbon input of straw. The amount of magnetized straw and magnetized biochar were adjusted according to their preparation yields, resulting in 2.67 and 1.63 g for the MCS and MBc treatments, respectively.

To ensure homogeneous mixing, a small portion of amendment and air-dried soil was first combined in a glass beaker using a plastic spoon. After thorough mixing, the remaining soil was gradually added and continuously mixed until a uniform soil amendment mixture was obtained (Shi et al., 2024). The CK, CS, and Bc treatments each included three replicates. Each of the MCS and MBc treatments had six replicates divided into two subgroups: three without magnetic residue separation (MCS-O and MBc-O) and three with magnetic residue separation prior to soil and parameter analyses (MCS-D and MBc-D). During incubation, soil moisture was maintained at 25% by frequent weighing and watering, and all samples were incubated at 30°C in a constant-temperature incubator.

The incubation began in April 2024, with destructive sampling at 30, 60, 180, and 360 d after the start. The samples from each treatment were retrieved, air-dried, and sieved through a 2 mm mesh for subsequent analyses.

2.3. Fractionation of POM and MAOM

SOM was fractionated into particulate organic matter (POM) and mineral-associated organic matter (MAOM) following the wet sieving and particle-size fractionation methods described by Cambardella and Elliott (1992). Specifically, 20 g of air-dried soil was weighed and mixed with 60 mL of 5 g L^{-1} sodium hexametaphosphate solution. The mixture was shaken for 18 h at 25°C and 180 rpm. The dispersed suspension was then passed through a 53 μm sieve and washed repeatedly with small volumes of deionized water until the filtrate became clear and colorless. The material retained on the sieve (>53 μm) was considered as sand particles and POM, while the fraction passing through the sieve (<53 μm) consisted of silt- and clay-sized particles along with MAOM.

The POM and MAOM fractions were collected separately in glass beakers. Within the soil-water suspension, a strong external magnetic iron rod was used to separate undecomposed magnetized straw and magnetized biochar residues from the POM and MAOM fractions in liquid form. These separated materials were designated as magnetized residue components within the POM and MAOM fractions, respectively. Both the soil fractions and magnetized residue fractions of POM and MAOM were dried at 60°C, weighed, and ground through a 60-mesh sieve (Liu et al., 2024). After the complete removal of undecomposed magnetized organic residues, the soil organic matter (*SOC*) content of the original soil and each fraction was determined using the potassium dichromate oxidation method with external heating (Nelson and Sommers, 1982). The organic carbon content of organic residue samples and soil fractions at different incubation times was measured using an elemental analyzer (Vario EL III, Hanau, Germany). Data were corrected on an ash-free and moisture-free basis (Ndzelu et al., 2021). The concentration of particulate organic carbon (*POC*) expressed in g kg^{-1} was calculated as follows:

$$POC = M_P \times OC_P \tag{1}$$

$$POM\ (\%) = POC\ /\ SOC \times 100 \tag{2}$$

where M_P denotes the relative mass proportion of the POM fraction (%), OC_P represents the organic carbon content of the POM fraction (g kg^{-1}), and *SOC* denotes the organic carbon content of the undisturbed soil in soil samples (g kg^{-1}).

2.4. Calculation of organic residue retention rate

The cumulative retention rate of dry matter from straw (CS) and biochar (Bc) residues within the MCS and MBc fractions was calculated as follows:

$$L(\%) = \frac{M_d - M_{Fe}}{M_1} \times 100\% \tag{3}$$

where *L* is the mass retention rate of the organic residue (%), M_d is the dry mass of the recovered magnetized material at different decomposition times (g), M_{Fe} is the dry mass of the Fe-related products in the applied magnetized material (g), and M_1 is the dry mass of the applied straw or biochar (g).

2.5. Data analysis

All data were preprocessed using Microsoft Excel 2022. Statistical analyses were performed using IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, USA).

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Differences between treatments were assessed using Duncan's multiple range test at a significance level of $p < 0.05$. Graphs were generated using Origin 2022.

3. Results and analysis

3.1. Differences between magnetized and original organic materials

As shown in Table 1, no significant differences were observed in the molar ratios of carbon to nitrogen (C/N), hydrogen to carbon (H/C), or oxygen to carbon (O/C) before and after magnetic modification of the organic materials. This result indicates that the magnetization process does not substantially alter the elemental composition of organic materials. The C/N, H/C, and O/C ratios serve as key indicators of the chemical properties and structural characteristics of organic materials. Specifically, the C/N ratio could be closely associated with the decomposition rate of organic substrates, the H/C ratio reflects aromaticity, and the O/C ratio represents the oxidation level (Ndzelu et al., 2021). The near-constant values of these ratios before and after magnetization suggest that the fundamental chemical attributes and structural features of the organic materials remained unchanged by magnetic treatment.

Therefore, the magnetized organic materials exhibited high chemical and structural consistency with their non-magnetized counterparts, making them reliable representatives of original organic substrates. This conclusion could present a sound theoretical basis for using magnetized organic materials in subsequent experiments to investigate the behavior of undecomposed organic residues in soil. It also ensured the reliability and accuracy of results related to the assessment of "false increases" in soil organic matter through the separation of

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magnetized organic residues.

Table 1 Comparison of elemental composition of organic materials before and after magnetization.

Treatment	N	C	H	O	C/N	H/C	O/C
	%				Ratio	Ratio	Ratio
CS	0.99	46.20	6.84	45.96	54.32	1.78	0.75
Bc	0.78	79.35	3.65	16.22	118.49	0.55	0.15
MCS	1.00	46.68	6.55	45.77	54.43	1.68	0.74
MBc	0.80	79.37	3.54	16.30	115.65	0.53	0.15

3.2. Temporal changes in magnetized organic residues in soil

As shown in Fig. 1, the retention rate of straw residues in MCS gradually decreased over the incubation period, with values of 85.98%, 63.00%, 58.99%, and 54.55% at 30, 60, 180, and 360 d, respectively. In contrast, the biochar fraction in MBc exhibited relatively minor changes, with retention rates of 98.92%, 97.88%, 94.80%, and 92.48% at the corresponding time points. These results indicate that the straw component in MCS underwent decomposition in soil and, with increasing incubation time, was eventually transformed into stabilized organic matter. Conversely, the biochar fraction in MBc demonstrated high stability and low decomposition in soil, suggesting that it could not represent truly decomposed organic matter.

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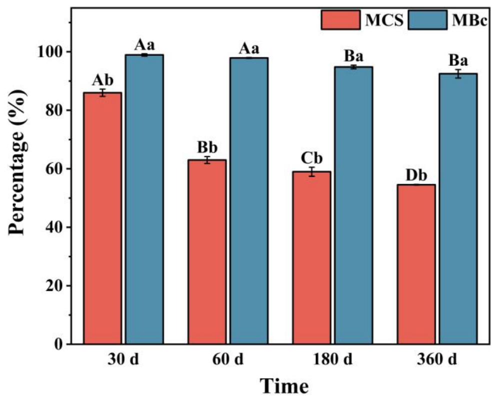

Fig. 1. Residual rates of undecomposed magnetized straw (MCS) and magnetized biochar (MBc) separated from soil at different incubation times.

Note: MCS refers to magnetized straw; MBc refers to magnetized biochar. Different uppercase letters indicate significant differences among sampling times within the same organic residue ($p<0.05$), while different lowercase letters indicate significant differences between organic residues at the same sampling time ($p<0.05$).

The results in Fig. 2 further demonstrate that the two types of magnetized organic materials differed not only in their retention rates but also in the extent of mass changes after decomposition. Compared with the soil MAOM fraction, undecomposed MCS residues in the early incubation stage exhibited higher H/C and C/N ratios, closer to those of the soil POM fraction. As shown in Fig. 2a, the H/C ratio of MCS residues decreased gradually over time, approaching that of MAOM by day 360, whereas the O/C ratio exhibited a slow increase. In contrast, these trends were not evident in MBc residue samples. A decrease in the H/C ratio indicates a reduced aliphatic character of the organic residues (Banach-Szott et al., 2014; Dou and Li, 2010), while an increase in the O/C ratio could reflect increased oxidation

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(Mohammed et al., 2023). These findings suggest that with prolonged incubation, the molecular conjugation of the organic residues increased, accompanied by changes in the electronic environment of oxygen-containing functional groups, thereby enhancing aromatic structural features. Fig. 2b illustrates that the C/N ratio and carbon concentration of MCS residues declined continuously, gradually approaching those of the soil MAOM fraction. This trend reflects the progressive humification of organic residues (Abakumov and Eskov, 2023), indicating an increasing degree of humification. Notably, the C/N ratio of MCS residues at 360 d approximated that of MAOM. Conversely, the changes in these parameters for MBc residues were relatively small, indicating that the organic components of MBc residues are more stable and less prone to decomposition and transformation.

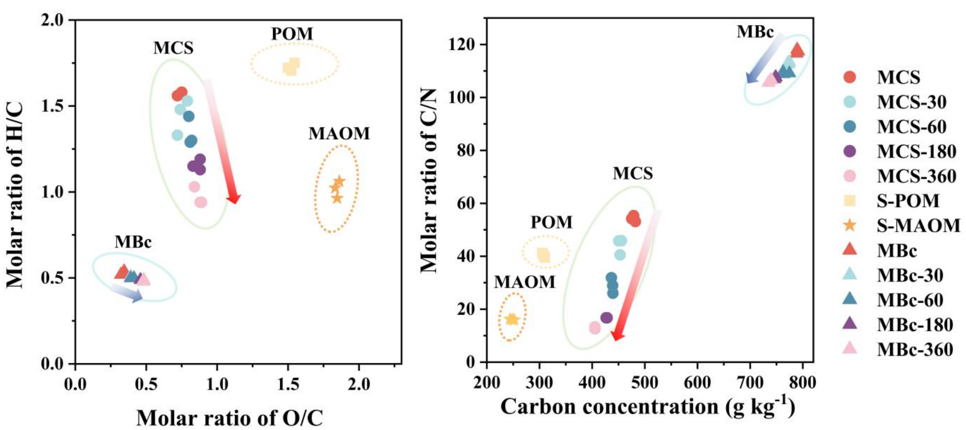

Fig. 2. Van Krevelen diagram of atomic H/C and O/C ratios (a), and comparison of C/N ratio and carbon concentration (b) of magnetized organic residues, soil POM, and MAOM fractions at different incubation times.

Note: MCS refers to magnetized straw; MBc refers to magnetized biochar. MCS-30, MCS-60, MCS-180, and MCS-360 represent undecomposed magnetized straw residues separated from

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soil at 30, 60, 180, and 360 days, respectively; MBc-30, MBc-60, MBc-180, and MBc-360 represent undecomposed magnetized biochar residues separated from soil at the same respective time points. S-POM and S-MAOM denote soil samples of particulate organic matter and mineral-associated organic matter fractions, respectively. All data are corrected on an ash-free and moisture-free basis.

3.3. Organic residues cause false increases in the mass proportion and organic carbon content of soil POM fraction

Fig. 3 presents the relative mass proportions of the soil POM fraction at different incubation times across treatments. Clear differences among treatments were evident. Notably, no significant differences were observed between the MCS-O and MBc-O treatments and the CS and Bc treatments at any sampling time, supporting the applicability of magnetized materials in soil applications.

At 30, 60, 180, and 360 d of incubation, the mass proportion of the POM fraction (M_P) in the CS treatment increased by 18.94%, 11.97%, 8.78%, and 7.05%, respectively, compared with CK. For the Bc treatment, the corresponding increases were 17.22%, 17.16%, 16.95%, and 16.83%, respectively. However, after the removal of magnetized organic residues from the soil, no significant changes in POM mass proportion were observed in the MCS-D and MBc-D treatments compared with CK. These results indicate that the increases in POM mass proportion in the CS and Bc treatments were “artificial elevations” caused by undecomposed organic residues. Further analysis revealed that in the CS treatment, this artificial elevation decreased gradually over time, stabilizing at approximately day 180, whereas in the Bc

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treatment, it remained nearly constant throughout the incubation period.

Similarly, at different time points, the organic carbon content of the POM fraction (OC_P) in the CS treatment increased by 37.87%, 26.99%, 15.94%, and 7.92%, respectively, compared with CK. For the Bc treatment, the increases were 35.86%, 33.83%, 31.93%, and 31.10%, respectively. At the same time points, the OC_P in the CS treatment exceeded that in the MCS-D treatment by 37.68%, 26.53%, 15.25%, and 7.48%, respectively. Moreover, the OC_P in the Bc treatment was higher than in the MBc-D treatment by 35.80%, 33.96%, 31.93%, and 31.10%. These results demonstrated that both the carbon content and mass proportion of the POM fraction exhibited a “false increase”. As no significant difference was identified between the MCS-D and CK treatments, the reduction in the false increase for the CS treatment was attributable not to an increase in organic carbon content in the MCS-D treatment but to the decomposition of organic residues within the fraction.

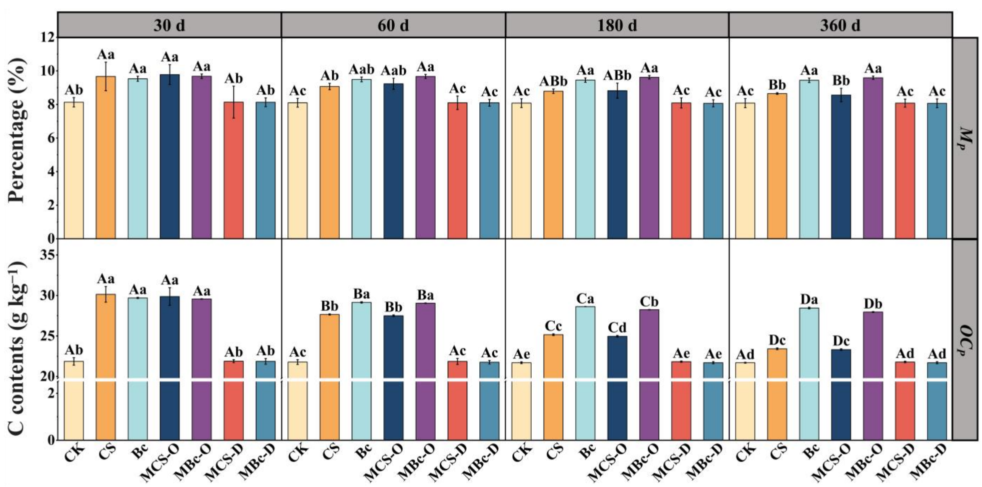

Fig. 3. Relative mass proportion (M_P) and organic carbon content (OC_P) of the soil POM fraction at different incubation times across treatments.

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Note: CK denotes the control treatment without organic amendments; CS denotes the treatment with normal straw application; Bc denotes the treatment with biochar applied at an equivalent carbon amount to straw; MCS denotes the treatment with magnetized straw applied at an equivalent carbon amount; and MBc denotes the treatment with magnetized biochar applied at an equivalent carbon amount. MCS-O and MBc-O refer to treatments in which magnetized organic materials were not removed at the end of incubation; MCS-D and MBc-D refer to treatments in which magnetized organic residues were separated from the soil before testing the remaining soil samples. Different uppercase letters indicate significant differences among sampling times within the same treatment, whereas different lowercase letters indicate significant differences among treatments at the same sampling time ($p<0.05$).

3.4. Organic residues cause false increases in POC and SOC contents

As shown in Fig. 4, the *POC* contents in the MCS-O and MBc-O treatments were slightly lower than those in the CS and Bc treatments, although the differences were not statistically significant. Specifically, at 30, 60, 180, and 360 d of incubation, the *POC* contents in both the CS and Bc treatments were significantly higher than those in CK. The increase in *POC* content compared with CK in the CS treatment showed a clear decreasing trend, with increases of 63.48%, 42.61%, 26.29%, and 16.00%, respectively. In contrast, although the *SOC* content in the Bc treatment also declined during incubation, the decrease was less pronounced, with increases of 58.99%, 57.38%, 54.86%, and 53.71% at the respective time points. No significant differences in *POC* content were observed between the MCS-D and MBc-D treatments, indicating that the elevated *POC* contents in the CS and Bc

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treatments originated from undecomposed organic residues. The *POC* contents in the CS treatment exceeded that in the MCS-D treatment by 63.48%, 41.80%, 24.86%, and 15.34% at the respective time points, whereas the *POC* contents in the Bc treatment were higher than that in the MBc-D treatment by 58.99%, 42.61%, 54.86%, and 53.71%, respectively.

Across all incubation periods, the *SOC* contents in the MCS-O and MBc-O treatments were comparable to those in the CS and Bc treatments, indicating strong consistency between the magnetized organic materials and the original organic materials during incubation. Specifically, at 30, 60, 180, and 360 d, the *SOC* contents in the CS and Bc treatments were significantly higher than in CK. The *SOC* content in the CS treatment showed a decreasing trend, with increases of 11.95%, 8.40%, 5.71%, and 4.50%, respectively. In contrast, although the *SOC* content in the Bc treatment also declined over time, the decrease was less pronounced, with increases of 12.41%, 12.35%, 10.89%, and 11.06% at the respective time points. After 360 d of incubation, the *SOC* content in the MCS-D treatment showed an increasing trend, whereas the *SOC* content in the MBc-D treatment remained similar to that in CK without significant changes, maintaining a relatively stable level throughout the incubation period.

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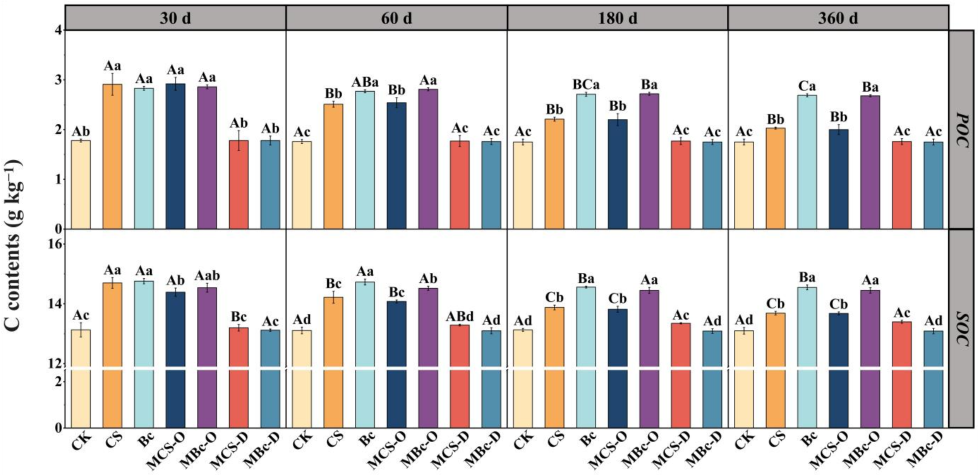

Fig. 4. *POC* and *SOC* contents of different treatments at various incubation times.

Note: CK denotes the control treatment without organic amendments; CS denotes the treatment with normal straw application; Bc denotes the treatment with biochar applied at an equivalent carbon amount to straw; MCS denotes the treatment with magnetized straw applied at an equivalent carbon amount; and MBc denotes the treatment with magnetized biochar applied at an equivalent carbon amount. MCS-O and MBc-O refer to treatments in which magnetized organic materials were not removed at the end of incubation; MCS-D and MBc-D refer to treatments in which magnetized organic residues were separated from the soil before testing the remaining soil samples. Different uppercase letters indicate significant differences among sampling times within the same treatment, whereas different lowercase letters indicate significant differences among treatments at the same sampling time ($p<0.05$).

3.5. Organic residues cause false increases in the proportion of POM in total SOM

As shown in Fig. 5, the proportion of POM to total SOM (*POC*/*SOC*) in the CS and Bc treatments was significantly higher than that in CK. At different incubation times, the ratios

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in the CS treatment increased by 46.23%, 31.05%, 19.31%, and 10.54%, whereas those in the Bc treatment increased by 41.58%, 39.60%, 39.15%, and 38.04%, respectively. However, the false elevation of the POM proportion in the SOM persisted. At different time points, the ratios in the CS treatment were 46.88%, 32.23%, 20.39%, and 12.47% higher than those in the MCS-D treatment, whereas in the Bc treatment, they were 41.47%, 39.70%, 38.94%, and 38.04% higher than those in the MBc-D treatment. Notably, the POM proportion in SOM in the MCS-D treatment was lower than that in CK, which was attributed to the greater conversion of straw residues into MAOM during decomposition, thereby increasing the MAOM proportion in SOM. In contrast, no significant changes were observed in biochar in the MBc-D treatment, and the proportion of POM in SOM was similar to that in CK.

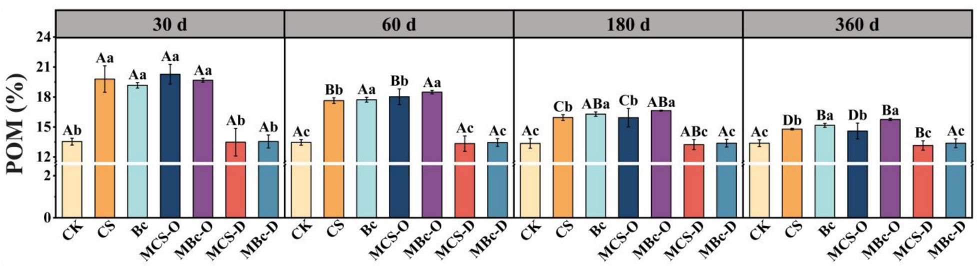

Fig. 5. Proportion of POM content in total SOM for different treatments at various incubation times.

Note: CK denotes the control treatment without organic amendments; CS denotes the treatment with normal straw application; Bc denotes the treatment with biochar applied at an equivalent carbon amount to straw; MCS denotes the treatment with magnetized straw applied at an equivalent carbon amount; and MBc denotes the treatment with magnetized biochar applied at an equivalent carbon amount. MCS-O and MBc-O refer to treatments in

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which magnetized organic materials were not removed at the end of incubation; MCS-D and MBc-D refer to treatments in which magnetized organic residues were separated from the soil before testing the remaining soil samples. Different uppercase letters indicate significant differences among sampling times within the same treatment, whereas different lowercase letters indicate significant differences among treatments at the same sampling time ($p<0.05$).

4. Discussion

4.1. Differences in the transformation of organic materials with different qualities in soil

As shown in Fig. 1, the proportion of undecomposed straw residues significantly decreased over different incubation periods, with a residue rate of only 54.55% after 360 d. In sharp contrast, biochar exhibited almost no decomposition, maintaining a high residue rate of 92.48%. Fig. 2 indicates that the molecular conjugation degree of magnetic straw residues was enhanced, with changes occurring in the electronic environment of oxygen-containing functional groups, which can strengthen the aromatic structure and stabilize the framework. The composition of organic residues may gradually shift towards humification (Yu et al., 2022), whereas MBc residues exhibit negligible changes throughout the incubation period. These outcomes can be attributed to the lower C/N ratio of straw compared with the relatively higher C/N ratio of biochar, which can cause greater reactivity and a faster mineralization rate, enabling straw to decompose more rapidly in soil (Chen et al., 2023). Chen et al. (2010) reported that after straw incorporation into soil, labile components rapidly decomposed within 0–60 d, followed by slower decomposition during 60–180 d, which can be consistent with the present findings. This could be because during the early decomposition

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stage, highly biodegradable components such as carbohydrates, organic acids, and amino acids are extensively consumed, while more recalcitrant components, such as aromatic and polymeric fractions, are retained (Ren et al., 2021). On the other hand, biochar is produced via pyrolysis of biomass at 300–700°C under high-pressure anaerobic conditions (Dungait et al., 2012). Through pyrolysis, the labile cellulose-C in straw can be converted into aromatic biochar-C, greatly enhancing its structural stability and resistance to rapid decomposition in soil (Yin et al., 2022), thus remaining largely as a residue (Bornø et al., 2019). As a carbon-rich soil amendment with slow decomposition and a surface conducive to organic molecule aggregation, biochar offers unique advantages for soil carbon sequestration and structural improvement (Cao et al., 2022; Fan et al., 2021; Wang et al., 2025; Zhang et al., 2024). When applied to soil, it can reduce bulk density (Zhang et al., 2021), increase porosity (He et al., 2022), alleviate acidification (Shi et al., 2023), retain moisture (Khaledi et al., 2023), and enhance nutrient absorption efficiency and nutrient cycling coordination (Burgeon et al., 2022). Owing to its porosity, alkalinity, strong adsorption capacity, and large specific surface area, biochar has been widely applied for environmental remediation and sustainable agricultural production (Papageorgiou et al., 2021; Pathy et al., 2023; Xu et al., 2021). Therefore, despite its slow decomposition in soil, its unique role in improving soil structure and function remains significant.

4.2. Residual undecomposed organic matter leads to a false increase in the POM fraction

The analysis of the weight proportion and organic carbon content of soil fractions presented in Figs. 3 and 4 clearly demonstrated that under the CS and Bc treatments, both the relative mass and organic carbon content of the POM fraction were consistently higher than

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those in the CK treatment. This finding aligns with those reported by Xie et al. (2014). The POM fraction mainly consists of partially decomposed, chemically recalcitrant polymeric structures, such as acid-insoluble fibers formed through fragmentation, which could primarily originate from organic materials. Owing to its rapid responsiveness to environmental changes, POM can be highly sensitive to agricultural management practices (Christensen, 1992; Cotrufo et al., 2022; Guo et al., 2022; Rocci et al., 2021; Witzgall et al., 2021). Xie et al. demonstrated that increasing the input of organic materials directly influenced both SOM content and its proportion within the POM fraction. They attributed this phenomenon to the continuous accumulation of organic residues in soil induced by organic amendments (Xie et al., 2014). However, residual undecomposed organic residues should not be equated with true organic matter, as treating these residues as part of SOM can lead to biased results and misinterpretation.

In this experiment, the POM mass proportion and organic carbon content for the MCS-D and MBc-D treatments were obtained by first applying the magnetic materials to the soil for a period of incubation, then extracting the magnetic residues from the soil, and subsequently testing the soil samples after removal of the undecomposed materials. The results showed that after the magnetic materials were extracted, the POM mass proportion and organic carbon content in the MCS and MBc treatments did not exhibit significant increases compared with the CK treatment. This proved that the increases in POM mass proportion and organic carbon content observed under the CS and Bc treatments were largely attributable to the direct input of straw and biochar materials, with most undecomposed organic residues remaining within the POM fraction. Moreover, the “false elevation” in both POM mass proportion and organic

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carbon content under the CS treatment decreased over the incubation period, whereas the corresponding values under the Bc treatment remained nearly constant. These findings suggest that the quantity, quality, and incubation duration of organic residues are key factors driving the increase in the POM mass proportion and organic carbon content. Additionally, the extent of increase in the POM fraction was closely related to the amount and source of organic material applied.

The results shown in Fig. 4 revealed a pronounced decreasing trend in the POM fraction organic carbon content (*POC*) under CS treatment. This confirmed that the effect of organic material addition in the short term was predominantly reflected in the POM fraction, whereas a gradual increase in the MAOM fraction was observed. This aligned with the conclusions of Bhattacharyya et al. (2011), Brown et al. (2014), and Stewart et al. (2012) who reported that organic amendments were primarily retained in the POM fraction, which could be more prone to mineralization, while gains in the MAOM fraction remained limited. The MAOM fraction in soil has been mainly formed over decades to centuries through long-term weathering processes involving interactions between organic matter and secondary minerals. Due to this extremely slow formation process, MAOM accumulation can be difficult to achieve in the short term (Kleber et al., 2007; Slessarev et al., 2022). Moreover, because microorganisms struggle to utilize chemically recalcitrant components within plant residues, decomposition of these highly processed structural organic residues and POM components has been reported to cause MAOM formation (Cotrufo et al., 2015). This explains why the organic carbon data for the Bc treatment in this study (Figs. 3 and 4) indicated that most undecomposed organic residues remained preserved within the POM fraction, thereby

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reducing the MAOM contribution to the soil. This also accounted for the consistently higher MAOM contribution observed in the CS and Bc treatments than in the MCS-D and MBc-D treatments.

Currently, some studies have suggested that abundant POM can be crucial for agroecosystem functioning and crop productivity, thereby advocating for greater research focusing on POM increments (Wood et al., 2016). However, the results of this study indicated that within the POM fraction, the dominant influencing factors were the quantity and quality of undecomposed organic residues, with temporal factors exerting a significant impact. Although the POM fraction plays an important role in nutrient supply, microbial activity promotion, and soil structure regulation, the indiscriminate addition of organic materials to soil primarily increases the amount of undecomposed organic residues, most of which reside in the POM fraction over short time periods. While this practice directly raises the measured SOM content, it represents a superficial increase, as the majority of SOM gain is derived from unstable undecomposed organic residues rather than stabilized organic matter. Considering the POM fraction as part of SOM without distinction carries inherent risks, as this “false elevation” can lead to the overestimation of global SOM content.

5. Conclusion

Based on the comprehensive results of this study, magnetic treatment exerted minimal influence on the elemental composition of organic materials, indicating that magnetized organic materials can serve as valid representatives of normal organic materials and that the related experimental outcomes are reliable. The straw component in MCS decomposed

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readily in soil, with its residue rate markedly decreasing during the incubation period. The H/C ratio of the residues decreased, the O/C ratio increased, and both the C/N ratio and carbon concentration decreased continuously, indicating reduced aliphaticity, enhanced oxidation, and a molecular structural shift toward increased aromaticity and greater humification. Furthermore, the proportion of residues in the POM fraction sharply declined with incubation time, approaching the characteristics of MAOM after 360 d. In contrast, the biochar component in MBc exhibited high stability in soil, showing minor changes in the residue rate, elemental ratios, and a relatively gradual decline in the proportion of the POM fraction, reflecting greater resistance to decomposition. After organic material incorporation, the unseparated residues in the CS and Bc treatments resulted in higher POM organic carbon content and a larger proportion of total SOM than in CK. However, this increase represented a "false elevation", most of which pronounced during the early incubation period. After residue separation, the MCS-D and MBc-D treatments displayed little difference from CK, indicating that the "false elevation" was primarily attributable to incompletely decomposed residues. On day 30, the false increases in *POC* content reached 63.48% and 58.99% for the CS and Bc treatments, respectively. Over time, the false elevation in CS gradually diminished, decreasing to 15.34% after 360 d, whereas the false elevation in Bc remained largely unchanged and stable, still reaching 53.71% after 360 d. Owing to the greater conversion of straw residues into MAOM during decomposition, the POM fraction contribution in MCS-D was lower than that in CK. Concurrently, biochar in MBc-D exhibited no significant change, with a POM contribution comparable to that of CK. These results confirmed the risk of overestimation of SOM when the POM fraction was fully counted, particularly because the long-term persistence of recalcitrant organic materials can cause systematic bias in global SOM content assessments. These findings could provide important references for the precise evaluation of soil organic matter transformation processes and contents.

Conflicts of Interest: The authors declare no conflict of interest.

CRediT authorship contribution statement： Yuhan Xia: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Sen Dou: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. Guan Song: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. Dilimulati Yalihong: Writing – review & editing, Methodology, Investigation.

Funding: This work was supported by the National Key Research and Development Program of China (2024YFD1500502-04).

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Preprint. Discussion started: 12 December 2025

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