

1 **Magnetic separation reveals overestimation of soil organic matter due to undecomposed**

2 **particulate residues**

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11 **Abstract**

12 Soil organic matter (SOM) is a complex mixture of organic compounds derived from the
13 decomposition of plant and animal residues. SOM that has undergone microbial
14 transformation and formed stable associations with minerals represents the stabilized fraction
15 of soil organic carbon, which differs from the simple physical accumulation of external
16 organic materials. Current understanding suggests that particulate organic matter (POM)
17 includes both undecomposed and partially decomposed residues. Conventional analytical
18 methods cannot clearly distinguish undecomposed external residues from native SOM.
19 Consequently, increases in operationally defined POM are often misinterpreted as evidence
20 of SOM stabilization or microbially transformed organic carbon formation. In this study,
21 straw and biochar were magnetized through chemical coprecipitation and applied to the soil.
22 Magnetic separation was performed at successive incubation times to isolate undegraded
23 magnetic residues, thereby enabling more accurate tracking of SOM dynamics. Five
24 treatments were established: blank control (CK), untreated straw (CS), untreated biochar with
25 carbon input equivalent to straw (Bc), magnetized straw (MCS), and magnetized biochar
26 (MBc). The recovery of magnetized straw residues declined continuously and reached
27 54.55% after 360 d, whereas biochar residues remained highly persistent at 92.48%. In the
28 CS and Bc treatments, the organic carbon content of POM fractions and their proportion in
29 total SOM were consistently higher than in CK, particularly during early incubation.
30 However, after removing undegraded residues by magnetic separation (MCS-D and MBc-D),
31 values were close to those of CK. This result indicates that the observed POM increases
32 mainly originated from undecomposed external residues rather than microbially stabilized

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33 SOM. On day 30, the apparent increase in particulate organic carbon (POC) was 63.48% in
34 CS and 58.99% in Bc. Over time, the apparent POC increase in CS declined to 15.34% by
35 day 360, whereas that in Bc remained high (53.71%). These findings suggest that interpreting
36 total POM as stabilized or microbially transformed SOM may lead to misleading conclusions
37 about SOM stability, particularly in short-term incubations or agroecosystems receiving fresh
38 organic amendments. This study provides a basis for a more accurate evaluation of soil
39 organic matter transformation dynamics and content.

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

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42 1. Introduction

43 Soil organic matter (SOM) is a complex assemblage of organic compounds formed
44 through the decomposition and transformation of plant and animal residues. It exhibits a
45 much stronger binding capacity to soil minerals than undecomposed or partially decomposed
46 residues. This strong binding makes it one of the most stable organic fractions in soil and
47 supports its long-term persistence. SOM originates from the partial microbial decomposition
48 of plant detritus (Angst et al., 2021; Cotrufo et al., 2013; Dou et al., 2020; Vendig et al.,
49 2023). Notably, the core of SOM refers to its labile and functional organic components with
50 dynamic transformation properties. These components supply nutrients to the soil, sustain
51 microbial activity, and regulate soil structure (Feng et al., 2025; Arumugam et al., 2025; Xu
52 et al., 2026). Therefore, SOM should not be regarded merely as the passive accumulation of
53 carbon-containing substances. Distinct SOM components exhibit different turnover rates and
54 stabilization mechanisms (Sokol et al., 2022; Von Lützow et al., 2007). Cambardella and
55 Elliott (1992) proposed a physical fractionation method based on particle size to isolate
56 particulate organic matter (POM) ranging from 2 mm to 53 μ m. Based on these fractions,
57 several conceptual models describing SOM formation and stabilization have been developed
58 (Christensen, 1992; Cotrufo and Lavallee, 2022; Guo et al., 2022; Lavallee et al., 2020; Rocci
59 et al., 2021; Witzgall et al., 2021).

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60 In recent years, soil management and improvement measures have primarily aimed to
61 increase organic material inputs and promote microbial utilization to form SOM (Cotrufo et
62 al., 2013; Castellano et al., 2015). However, when application rates exceed microbial
63 decomposition capacity, substantial amounts of undecomposed organic material can

64 accumulate in POM over a certain period (Bhattacharyya et al., 2011; Brown et al., 2014;
65 Stewart et al., 2012), leading to sharp short-term increases in POM organic carbon content
66 (Hua et al., 2022; Liang et al., 2016; Mitchell et al., 2018). This increase is “spurious”, as
67 POM remains susceptible to decomposition and transformation even under the physical
68 protection of soil (Connell et al., 2025), and such short-term increases are unstable (Janzen,
69 2015; Powlson et al., 2014). Currently, an accurate assessment of the proportion and duration
70 of this “spurious increase” in POM mass and organic carbon content at various times
71 following organic material application is still lacking.

72 In routine experiments, methods such as heavy liquid separation, sieving, and
73 electrostatic attraction can isolate some undecomposed organic materials. However, they are
74 less effective for highly fragmented materials such as biochar, limiting evaluation of SOM
75 transformation processes. Therefore, new approaches for efficient separation of
76 undecomposed residues are required. Magnetized materials (e.g., iron-based materials such as
77 nano-zero-valent iron and iron sulfides) can be rapidly separated from soil under an external
78 magnetic field, enabling the efficient recovery of target substances (Li et al., 2024; Rana et al.,
79 2025; Zhang et al., 2025). Although biochar modified with magnetized materials has been
80 widely studied, most research has focused on heavy metal or pollutant adsorption, with no
81 application in SOM transformation. Among magnetized material preparation methods, the
82 chemical coprecipitation method has been widely used because of its operational simplicity,
83 high efficiency, and ease of impurity removal (Zhou et al., 2019). It offers excellent
84 biocompatibility, stability, and recyclability (Baragaño et al., 2020; Duan et al., 2022), which
85 facilitate the combined application of organic materials in soil. [Iron particles form stable](#)

86 chemical bonds with organic materials, rather than simple physical adsorption. The surfaces
87 of these materials contain abundant oxygen-containing functional groups such as hydroxyl,
88 carboxyl, and carbonyl groups. During coprecipitation, these groups react with Fe²⁺ and Fe³⁺
89 to form coordinated and covalent bonds (Zhou et al., 2019; Duan et al., 2022). The resulting
90 magnetic nanoparticles are uniformly embedded within the porous structure of the organic
91 materials. This embedding prevents their detachment under non-biodegradation conditions,
92 such as physical disturbance or soil hydration. When soil microorganisms decompose organic
93 components, including cellulose, hemicellulose, and lignin, the functional groups that bind
94 iron particles are disrupted. As a result, magnetic nanoparticles detach or disperse into
95 non-magnetic fine particles smaller than 10 nm, which cannot be captured by magnetic fields.
96 Consequently, decomposed residues completely lose their magnetism (Li et al., 2024).

97 In this study, a chemical coprecipitation method was used to composite straw (CS) and
98 straw biochar (Bc) into magnetized materials. At different incubation stages, undecomposed
99 magnetized organic residues were separated using an external magnetic field to eliminate
100 their interference in SOM determination. This approach allowed the accurate achievement of
101 three objectives: (i) to quantify and characterize the incompletely decomposed residues at
102 different times after organic material application; (ii) to determine the existence, proportion,
103 and duration of a “spurious increase” in POM organic carbon; and (iii) to assess the
104 proportion of organic residues ultimately transformed into stable SOM. The results provide
105 critical support for precise evaluation of POM organic carbon content and elucidation of the
106 mechanisms by which organic materials are transformed into stable SOM.

107

110 2. Materials and Methods

111 2.1. Experimental materials

112 The test soil was collected from the experimental station of Jilin Agricultural University,
113 located in the semi-humid region of Northeast China (43°48'43.57"N, 125°23'38.50"E). The
114 region has a temperate semi-humid climate, with an annual mean temperature of 4.6°C and
115 average annual precipitation ranging from 600 to 700 mm. The soil is classified as Black Soil
116 under the suborder of semi-moist temperature semi-eluvial soil in the Chinese soil
117 classification system, which is equivalent to Argiudolls in the USDA soil taxonomy. In
118 September 2023, 100 soil samples were randomly collected from the 0–20 cm layer using a
119 soil auger and combined to form a composite sample. After sampling, visible organic
120 residues were manually removed. The field-moist soil was air-dried and sieved through a 2
121 mm mesh for subsequent incubation. The basic properties of the soil were determined prior to
122 the formal experiment as part of the initial soil characterization, with specific measurement
123 methods following standard protocols in soil science: soil organic matter was determined by
124 the dichromate oxidation method, total nitrogen by the Kjeldahl method, available nitrogen
125 by the alkaline hydrolysis-diffusion method, available phosphorus by the
126 molybdenum-antimony colorimetric method, and available potassium by flame photometry.
127 The specific values were as follows: soil organic matter, 22.76 g kg⁻¹; total nitrogen, 1.28 g
128 kg⁻¹; available nitrogen, 132.21 mg kg⁻¹; available phosphorus, 18.52 mg kg⁻¹; and available
129 potassium, 99.32 mg kg⁻¹.

130 The corn stover (CS) used in the experiment was obtained from the Experimental
131 Station of the Jilin Agricultural University, Jilin Province, China (Changchun, China). The

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130 entire CS was rinsed with deionized water to remove surface ash and soil, dried in an oven
131 for 24 h, ground using a grinder, and sieved through a 20-mesh sieve for later use.

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

136 The magnetized straw (MCS) and magnetized biochar (MBc) were prepared using the
137 chemical coprecipitation method (Zhou et al., 2019) as follows: 2.5 g of FeCl₃·6H₂O and 1.5
138 g of FeSO₄·7H₂O (Fe³⁺:Fe²⁺ molar ratio of 2:1) were weighed into a beaker. Subsequently,
139 2.0 g of dried CS or Bc was introduced to 100 mL of ultrapure water. The mixture was
140 thoroughly stirred at room temperature for 30 s using a magnetic stirrer. An excess of
141 ammonia solution (NH₃·H₂O) was subsequently added to adjust the pH to 10. After the
142 reaction, the magnetic materials in the suspension were separated from the liquid phase using
143 an external magnet. The magnetized samples were collected, dried in a vacuum oven at 60°C,
144 weighed, and designated as magnetized straw (MCS) and magnetized biochar (MBc).

145

146 *2.2. Experimental Design*

147 Prior to the incubation experiment, the collected soil was pretreated by thorough mixing
148 and sieving through a 2 mm mesh. Fine roots and other visible plant residues were carefully
149 removed, and all iron-containing particles were extracted using a magnetic rod to minimize
150 potential experimental interference. The study included five treatments: (1) control (CK): no
151 organic amendment; (2) straw treatment (CS): non-magnetized straw; (3) biochar treatment

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

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

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

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

174

175 2.3. Fractionation of POM and MAOM

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

185 The POM and MAOM fractions were collected separately in glass beakers. Within the
186 soil-water suspension, a strong external magnetic iron rod was used to separate
187 undecomposed magnetized straw and magnetized biochar residues from the POM and
188 MAOM fractions in liquid form. These separated materials were designated as magnetized
189 residue components within the POM and MAOM fractions, respectively. Both the soil
190 fractions and magnetized residue fractions of POM and MAOM were dried at 60°C, weighed,
191 and ground through a 60-mesh sieve (Liu et al., 2024). After the complete removal of
192 undecomposed magnetized organic residues, the soil organic carbon (SOC) content of the
193 original soil and each fraction was determined using the potassium dichromate oxidation
194 method with external heating (Nelson and Sommers, 1982). For preliminary soil
195 characterization, the organic carbon content of the original soil was first determined using the

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196 dichromate oxidation method. To ensure consistent and accurate measurements across all
 197 sample types, the organic carbon content of organic residue samples, the original soil, and
 198 soil fractions collected at different incubation stages was subsequently measured with an
 199 elemental analyzer (Vario EL III, Hanau, Germany). All organic carbon data reported in this
 200 study were obtained from elemental analysis and corrected for an ash-free and moisture-free
 201 basis (Ndzelu et al., 2021). To quantify the particulate organic carbon (POC) derived from
 202 amendment residues and its contribution to total soil organic carbon (SOC), the following
 203 equations were applied:

$$POC = M_p / 100 \times OC_p \quad (1)$$

$$POM - C \text{ Contribution} (\%) = POC / SOC \times 100 \quad (2)$$

206 where MP denotes the relative mass proportion of the POM fraction (% , i.e., percentage by
 207 mass of POM in the soil sample), OCP represents the organic carbon content of the POM
 208 fraction (g kg⁻¹), POC refers to the calculated particulate organic carbon content of the soil
 209 sample (g kg⁻¹), SOC denotes the total soil organic carbon content of the undisturbed soil (g
 210 kg⁻¹), and POM-C Contribution (%) represents the percentage contribution of particulate
 211 organic carbon to total soil organic carbon.

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213 2.4. Calculation of organic residue retention rate

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

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

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

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217 where L is the mass retention rate of the organic residue (%), M_d is the dry mass of the

218 recovered magnetized material at different decomposition times (g), M_{Fe} is the dry mass of
219 the Fe-related products in the applied magnetized material (g), and M_I is the dry mass of the
220 unmagnetized straw or biochar applied in the CS and Bc treatments (g). For the magnetized
221 treatments (MCS and MBc), the applied mass of magnetized materials was calculated based
222 on the same M_I to ensure equal organic carbon input across all treatments.

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223

224 2.5. Data analysis

225 All data were first organized using Microsoft Office Excel 2022, followed by statistical
226 analysis with IBM SPSS Statistics 25 (IBM Corporation, Armonk, NY, USA). One-way
227 analysis of variance (ANOVA) was performed to examine differences in the measured
228 indices across all treatments and incubation time points, with post-hoc multiple comparisons
229 conducted using the least significant difference (LSD) test at the 0.05 significance level.
230 Additionally, two-way ANOVA was applied to evaluate the effects of treatment, incubation
231 time, and their interaction on soil and fraction-specific organic carbon contents, and Duncan's
232 multiple range test (integrated in SPSS) was used for post-hoc comparison of significant
233 differences. Graphs were generated using Origin 2022.

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234

235 3. Results and analysis

236 3.1. Differences between magnetized and original organic materials

237 As shown in Table 1, no significant differences were observed in the molar ratios of
238 carbon to nitrogen (C/N), hydrogen to carbon (H/C), or oxygen to carbon (O/C) before and
239 after magnetic modification of the organic materials. This result indicates that the

240 magnetization process does not substantially alter the elemental composition of organic
241 materials. The C/N, H/C, and O/C ratios serve as key indicators of the chemical properties
242 and structural characteristics of organic materials. Specifically, the C/N ratio could be closely
243 associated with the decomposition rate of organic substrates, the H/C ratio reflects
244 aromaticity, and the O/C ratio represents the oxidation level (Ndzelu et al., 2021). The
245 near-constant values of these ratios before and after magnetization suggest that the
246 fundamental chemical attributes and structural features of the organic materials remained
247 unchanged by magnetic treatment.

248 The metallic nanoparticles produced by coprecipitation were uniformly distributed on
249 the surfaces of straw and biochar within a narrow size range. They formed a discontinuous
250 and porous coating, rather than a dense and impermeable layer. This nanoscale coating does
251 not block surface functional groups or internal pore structures, thereby preserving the natural
252 accessibility of organic materials to soil microorganisms (Panda et al., 2026). As a result, the
253 decomposition behavior of the magnetized materials remained consistent with that of the
254 unmodified materials, supporting their reliability in tracking SOM transformation processes.

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

262

263 **Table 1** Comparison of elemental composition of organic materials before and after
 264 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

265

266 3.2. Temporal changes in magnetized organic residues in soil

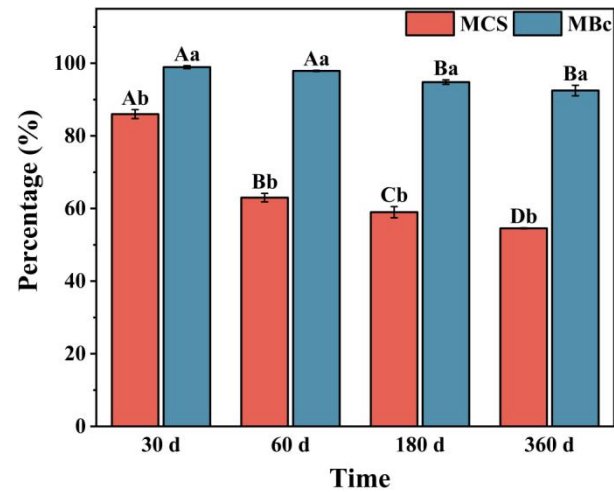
267 As shown in Fig. 1, the retention rate of straw residues in MCS gradually decreased over
 268 the incubation period, with values of 85.98%, 63.00%, 58.99%, and 54.55% at 30, 60, 180,
 269 and 360 d, respectively. In contrast, the biochar fraction in MBc exhibited relatively minor
 270 changes, with retention rates of 98.92%, 97.88%, 94.80%, and 92.48% at the corresponding
 271 time points. These results indicate that the straw component in MCS underwent
 272 decomposition in soil and, with increasing incubation time, was eventually transformed into
 273 stabilized organic matter. Conversely, the biochar fraction in MBc was significantly more
 274 resistant to microbial decomposition and more persistent than straw throughout the
 275 experiment, as evidenced by its consistently higher residue rate (92.48% at 360 d) compared
 276 to straw (54.55% at 360 d).

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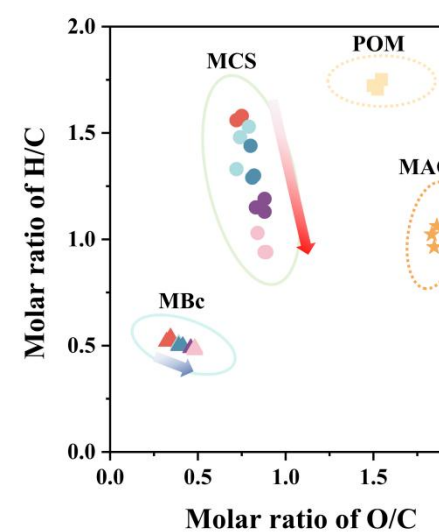
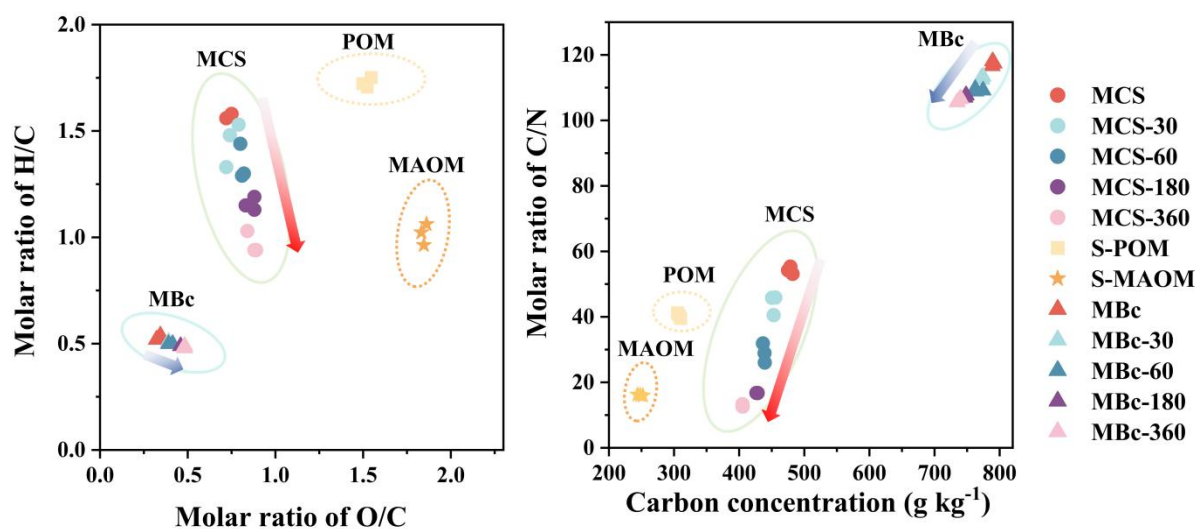
278
 279 **Fig. 1.** Residual rates of undecomposed magnetized straw (MCS) and magnetized biochar
 280 (MBc) separated from soil at different incubation times.

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

285
 286 The results in Fig. 2 further demonstrate that the two types of magnetized organic
 287 materials differed not only in their retention rates but also in the extent of mass changes after
 288 decomposition. Compared with the soil MAOM fraction, undecomposed MCS residues in the
 289 early incubation stage exhibited higher H/C and C/N ratios, closer to those of the soil POM
 290 fraction. As shown in Fig. 2a, the H/C ratio of MCS residues decreased gradually over time,
 291 approaching that of MAOM by day 360, whereas the O/C ratio exhibited a slow increase. In
 292 contrast, these trends were not evident in MBc residue samples. A decrease in the H/C ratio
 293 indicates a reduced aliphatic character of the organic residues (Banach-Szott et al., 2014; Dou
 294 and Li, 2010), while an increase in the O/C ratio could reflect increased oxidation

(Mohammed et al., 2023). These findings indicate that with prolonged incubation, shifts in the H/C and O/C ratios of the organic residues (evident from the bulk elemental analysis presented in Fig. 2) are consistent with oxidative transformation and changes in aliphatic content and structural condensation of the organic material. Fig. 2b further shows 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 decomposition and transformation of organic residues toward chemical characteristics similar to those of native soil mineral-associated organic matter, consistent with observations of organic matter stabilization in previous studies (Abakumov and Eskov, 2023). 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 were more resistant to microbial decomposition and transformation than straw residues within the 360-day incubation period.

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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

312 fractions at different incubation times.

313 Note: MCS refers to magnetized straw; MBc refers to magnetized biochar. MCS-30, MCS-60,
314 MCS-180, and MCS-360 represent undecomposed magnetized straw residues separated from
315 soil at 30, 60, 180, and 360 days, respectively; MBc-30, MBc-60, MBc-180, and MBc-360
316 represent undecomposed magnetized biochar residues separated from soil at the same
317 respective time points. S-POM and S-MAOM denote soil samples of particulate organic
318 matter and mineral-associated organic matter fractions, respectively. All data are corrected on
319 an ash-free and moisture-free basis.

320

321 *3.3. Organic residues cause false increases in the mass proportion and organic carbon*
322 *content of soil POM fraction*

323 Fig. 3 presents the relative mass proportions of the soil POM fraction at different
324 incubation times across treatments. Clear differences among treatments were evident.

325 Two-way ANOVA (Table S1) revealed that the relative mass proportion of the POM fraction
326 (MP) was significantly affected by treatment ($P < 0.001$) and incubation time ($P < 0.01$), with
327 no significant interaction between treatment and time ($P > 0.05$). Similarly, the organic
328 carbon content of the POM fraction (OC_P) was significantly influenced by treatment ($P <$
329 0.001), incubation time ($P < 0.001$), and their interaction ($P < 0.001$). Notably, no significant
330 differences were observed between the MCS- $\bar{\bar{O}}$ and MBc- $\bar{\bar{O}}$ (magnetized treatments
331 without removing magnetic organic residues at harvest) and the CS and Bc treatments at any
332 sampling time, supporting the applicability of magnetized materials in soil applications.

333 At 30, 60, 180, and 360 d of incubation, the mass proportion of the POM fraction (MP)

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334 in the CS treatment increased by 18.94%, 11.97%, 8.78%, and 7.05%, respectively, compared
335 with CK. For the Bc treatment, the corresponding increases were 17.22%, 17.16%, 16.95%,
336 and 16.83%, respectively. However, after the removal of magnetized organic residues from
337 the soil, no significant changes in POM mass proportion were observed in the MCS-D and
338 MBc-D (magnetized treatments with magnetic organic residues removed before analysis)
339 treatments compared with CK. These results indicate that the increases in POM mass
340 proportion observed in the CS and Bc treatments were residue-driven increases, arising from
341 the retention of persistent amendment residues within the operationally defined >53 μm
342 particulate fraction. Further analysis revealed that in the CS treatment, this artificial elevation
343 decreased gradually over time, stabilizing at approximately day 180, whereas in the Bc
344 treatment, it remained nearly constant throughout the incubation period.

345 Similarly, at different time points, the organic carbon content of the POM fraction (OC_P)
346 in the CS treatment increased by 37.87%, 26.99%, 15.94%, and 7.92%, respectively,
347 compared with CK. For the Bc treatment, the increases were 35.86%, 33.83%, 31.93%, and
348 31.10%, respectively. At the same time points, the OC_P in the CS treatment exceeded that in
349 the MCS-D treatment by 37.68%, 26.53%, 15.25%, and 7.48%, respectively. Moreover, the
350 OC_P in the Bc treatment was higher than in the MBc-D treatment by 35.80%, 33.96%,
351 31.93%, and 31.10%. These results demonstrated that both the carbon content and mass
352 proportion of the POM fraction exhibited residue-driven increases, resulting from the
353 retention of persistent amendment residues within the operationally defined >53 μm
354 particulate fraction. As no significant difference was identified between the MCS-D and CK
355 treatments, the reduction in the false increase for the CS treatment was attributable not to an

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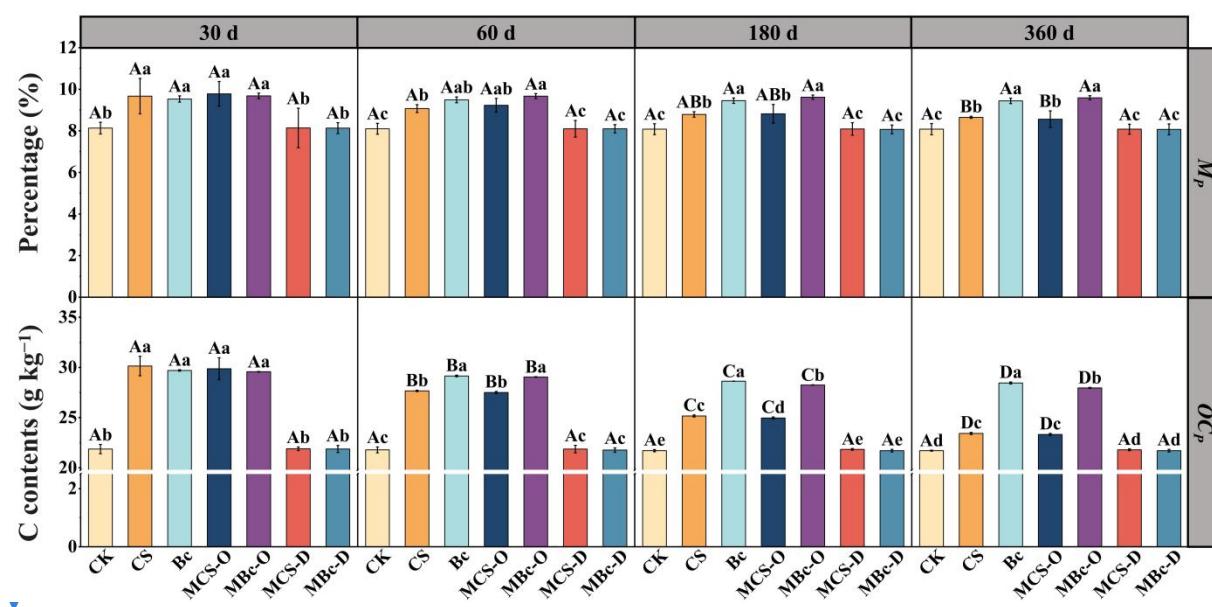
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356 increase in organic carbon content in the MCS-D treatment but to the decomposition of
 357 organic residues within the fraction.

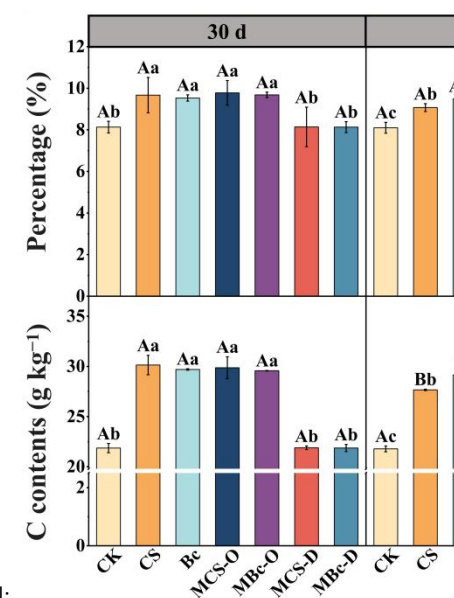
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359

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

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



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373 3.4. Organic residues cause false increases in POC and SOC contents

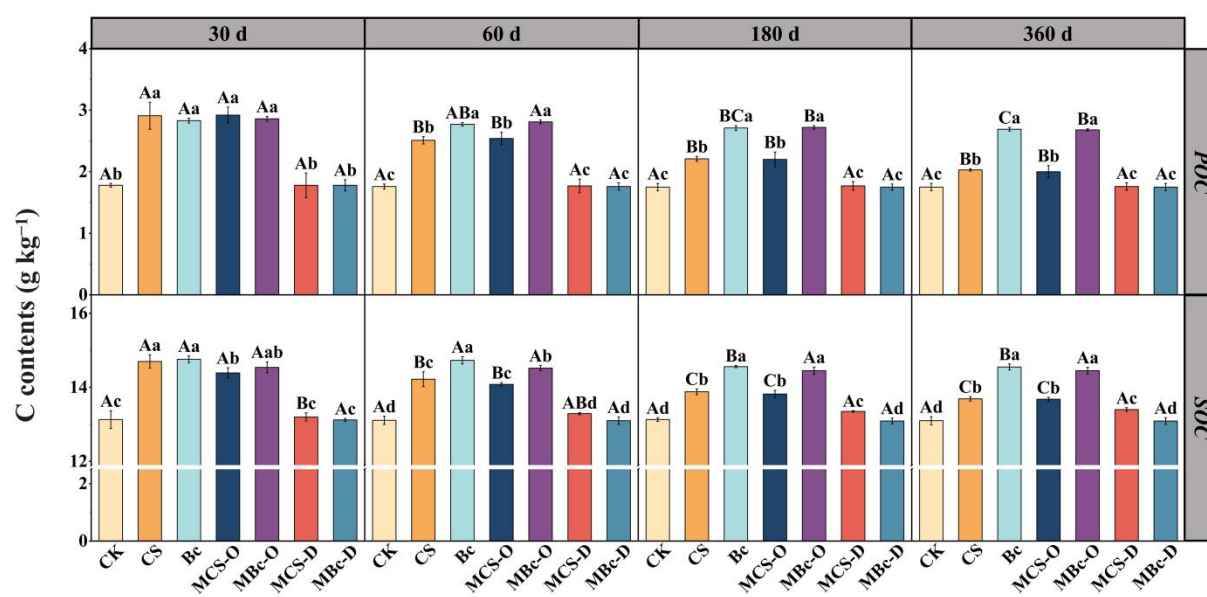
374 As shown in Fig. 4 and Table S2, two-way ANOVA indicated that the POC content was
375 significantly affected by treatment ($P < 0.001$), incubation time ($P < 0.001$), and their
376 interaction ($P < 0.001$). Similarly, the SOC content was significantly influenced by treatment
377 ($P < 0.001$), incubation time ($P < 0.001$), and their interaction ($P < 0.001$). The POC contents
378 in the MCS-O and MBc-O treatments were slightly lower than those in the CS and Bc
379 treatments, although the differences were not statistically significant. Specifically, at 30, 60,
380 180, and 360 d of incubation, the POC contents in both the CS and Bc treatments were
381 significantly higher than those in CK. The increase in POC content compared with CK in the
382 CS treatment showed a clear decreasing trend, with increases of 63.48%, 42.61%, 26.29%,
383 and 16.00%, respectively. In contrast, although the SOC content in the Bc treatment also
384 declined during incubation, the decrease was less pronounced, with increases of 58.99%,
385 57.38%, 54.86%, and 53.71% at the respective time points. No significant differences in POC
386 content were observed between the MCS-D and MBc-D treatments, indicating that the
387 elevated POC contents in the CS and Bc treatments originated from undecomposed organic
388 residues. The POC contents in the CS treatment exceeded that in the MCS-D treatment by
389 63.48%, 41.80%, 24.86%, and 15.34% at the respective time points, whereas the POC
390 contents in the Bc treatment were higher than that in the MBc-D treatment by 58.99%,
391 42.61%, 54.86%, and 53.71%, respectively.

392 Across all incubation periods, the SOC contents in the MCS-O and MBc-O treatments
393 were comparable to those in the CS and Bc treatments, indicating strong consistency between

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

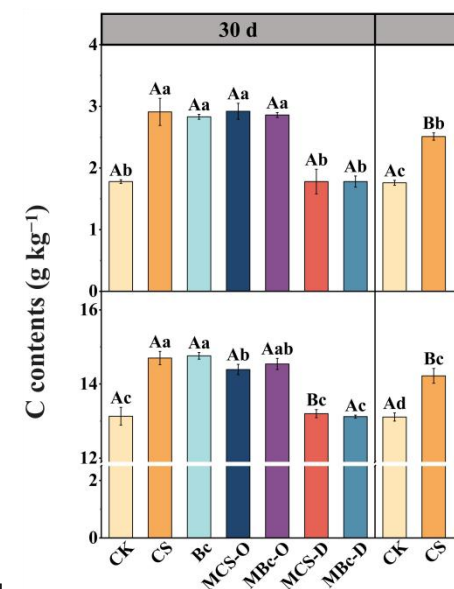
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405

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

407 Note: CK denotes the control treatment without organic amendments; CS denotes the
 408 treatment with normal straw application; Bc denotes the treatment with biochar applied at an
 409 equivalent carbon amount to straw; MCS denotes the treatment with magnetized straw



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410 applied at an equivalent carbon amount; and MBc denotes the treatment with magnetized
411 biochar applied at an equivalent carbon amount. MCS-O and MBc-O refer to treatments in
412 which magnetized organic materials were not removed at the end of incubation; MCS-D and
413 MBc-D refer to treatments in which magnetized organic residues were separated from the soil
414 before testing the remaining soil samples. Different uppercase letters indicate significant
415 differences among sampling times within the same treatment, whereas different lowercase
416 letters indicate significant differences among treatments at the same sampling time ($p < 0.05$).

417

418 3.5. Organic residues cause false increases in the proportion of POM in total SOM

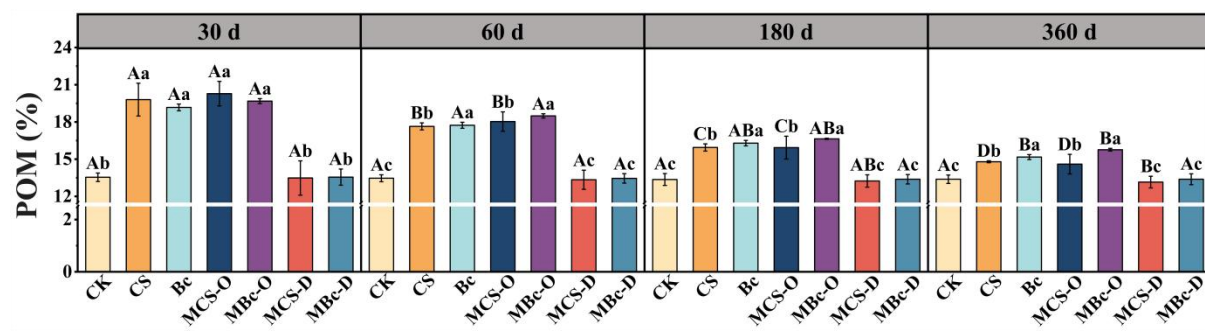
419 As shown in Fig. 5 and Table S3, two-way ANOVA revealed that the contribution of
420 POC to total SOC (POM-C contribution, POC/SOC) was significantly affected by treatment
421 ($P < 0.001$), incubation time ($P < 0.001$), and their interaction ($P < 0.001$). The proportion of
422 POC to total SOC (POC/SOC) in the CS and Bc treatments was significantly higher than that
423 in CK. At different incubation times, the ratios in the CS treatment increased by 46.23%,
424 31.05%, 19.31%, and 10.54%, whereas those in the Bc treatment increased by 41.58%,
425 39.60%, 39.15%, and 38.04%, respectively. However, the false elevation of the POM
426 proportion in the SOM persisted. At different time points, the ratios in the CS treatment were
427 46.88%, 32.23%, 20.39%, and 12.47% higher than those in the MCS-D treatment, whereas in
428 the Bc treatment, they were 41.47%, 39.70%, 38.94%, and 38.04% higher than those in the
429 MBc-D treatment. Notably, the POM proportion in SOM in the MCS-D treatment was lower
430 than that in CK, which was attributed to the greater conversion of straw residues into MAOM
431 during decomposition, thereby increasing the MAOM proportion in SOM. In contrast, no

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432 significant changes were observed in biochar in the MBc-D treatment, and the proportion of
 433 POM in SOM was similar to that in CK.

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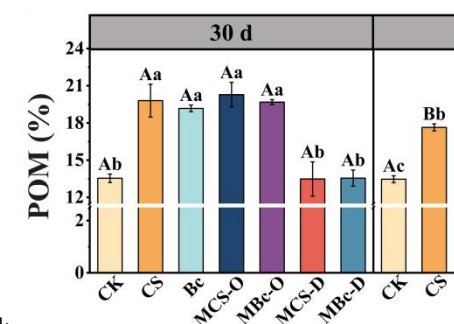
436 **Fig. 5. Proportion of POM-C contribution (POC/SOC) for different treatments at various**
 437 **incubation times.**

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

448

449 4. Discussion

450 4.1. Differences in the transformation of organic materials with different qualities in soil



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451 As shown in Fig. 1, the proportion of undecomposed straw residues significantly
452 decreased over different incubation periods, with a residue rate of only 54.55% after 360 d. In
453 sharp contrast, biochar exhibited almost no decomposition, maintaining a high residue rate of
454 92.48%. Based on the bulk elemental analysis in Fig. 2, the H/C and O/C ratios of magnetic
455 straw residues shifted with incubation time, which is consistent with oxidative transformation
456 and increased structural condensation of organic components, reflecting a gradual shift
457 toward more stable chemical characteristics, whereas MBc residues exhibit negligible
458 changes in elemental composition throughout the incubation period.

459 The contrasting decomposition dynamics between straw and biochar are primarily
460 driven by their inherent structural differences. Straw contains abundant labile components
461 (e.g., carbohydrates, organic acids, and amino acids) that are readily utilized by soil
462 microorganisms, leading to rapid mineralization within 0–60 d, followed by slower
463 decomposition of recalcitrant aromatic and polymeric fractions during 60–180 d, which
464 aligns with the present findings and previous reports (Chen et al., 2010; Ren et al., 2021). In
465 contrast, biochar is produced via pyrolysis of biomass at 300–700°C under anaerobic
466 conditions (Dungait et al., 2012); during this process, labile cellulose-C in straw is converted
467 into aromatic biochar-C with highly condensed structures, greatly enhancing its structural
468 stability and resistance to microbial decomposition in soil (Yin et al., 2022), thus enabling
469 biochar to remain largely as a residue (Bornø et al., 2019). Although straw has a lower C/N
470 ratio than biochar, this difference is a secondary feature accompanying their distinct chemical
471 structures, rather than the dominant factor controlling their decomposition rates.

472 The high stability of biochar observed in this study confirms its unique advantages as a

删除[Yuhan Xia]: 2 indicates that
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删除[Yuhan Xia]: was enhanced,
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删除[Yuhan Xia]: stabilize the framework. The composition
删除[Yuhan Xia]: residues may gradually
删除[Yuhan Xia]: towards humification (Yu et al., 2022)
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删除[Yuhan Xia]: a faster mineralization rate, enabling st
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删除[Yuhan Xia]: reported
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473 carbon-rich soil amendment for soil carbon sequestration and structural improvement, which
474 is consistent with previous studies (Cao et al., 2022; Fan et al., 2021; Wang et al., 2025;
475 Zhang et al., 2024). Characterized by slow decomposition and a surface conducive to organic
476 molecule aggregation, biochar can effectively reduce soil bulk density (Zhang et al., 2021),
477 increase soil porosity (He et al., 2022), alleviate soil acidification (Shi et al., 2023), retain soil
478 moisture (Khaledi et al., 2023), and enhance nutrient absorption efficiency and nutrient
479 cycling coordination (Burgeon et al., 2022) when applied to soil. Therefore, despite its slow
480 decomposition in soil, biochar plays a significant role in improving soil structure and function,
481 which is further supported by its high persistence observed in the present one-year incubation
482 experiment.

483 *4.2. Residual undecomposed organic matter contributes to increases in the POM fraction*

484 The analysis of the weight proportion and organic carbon content of soil fractions
485 presented in Figs. 3 and 4 clearly demonstrated that under the CS and Bc treatments, both the
486 relative mass and organic carbon content of the POM fraction were consistently higher than
487 those in the CK treatment. This finding aligns with those reported by Xie et al. (2014). The
488 POM fraction, a valid component of soil organic matter (SOM), mainly consists of partially
489 decomposed, chemically recalcitrant polymeric structures, such as acid-insoluble fibers
490 formed through fragmentation, which could primarily originate from exogenous organic
491 materials. Owing to its rapid responsiveness to environmental changes, POM can be highly
492 sensitive to agricultural management practices (Christensen, 1992; Cotrufo et al., 2022; Guo
493 et al., 2022; Rocci et al., 2021; Witzgall et al., 2021). Xie et al. demonstrated that increasing
494 the input of organic materials directly influenced both SOM content and its proportion within

删除[Yuhan Xia]: with slow decomposition and a surface conducive to organic molecule aggregation, biochar offers unique advantages

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删除[Yuhan Xia]:). Owing to its porosity, alkalinity, strong adsorption capacity, and large specific surface area, biochar has been widely

删除[Yuhan Xia]: for environmental remediation and sustainable agricultural production (Papageorgiou et al., 2021; Pathy et al., 2023; Xu et al., 2021)

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495 the POM fraction. They attributed this phenomenon to the continuous accumulation of
496 organic residues in soil induced by organic amendments (Xie et al., 2014). However, it is
497 critical to distinguish between POM derived directly from undecomposed amendment
498 residues and POM formed through microbial transformation of organic materials. This
499 distinction clarifies the dynamic nature of SOM accumulation. It does not imply that
500 residue-derived POM is an invalid component of SOM.

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misinterpretation

501 In this experiment, the POM mass proportion and organic carbon content for the MCS-D
502 and MBc-D treatments were obtained by first applying the magnetic materials to the soil for a
503 period of incubation, then extracting the magnetic residues from the soil, and subsequently
504 testing the soil samples after removal of the undecomposed materials. The results showed that
505 after the magnetic materials were extracted, the POM mass proportion and organic carbon
506 content in the MCS and MBc treatments did not exhibit significant increases compared with
507 the CK treatment. This proved that the increases in POM mass proportion and organic carbon
508 content observed under the CS and Bc treatments were largely attributable to the direct input
509 of straw and biochar materials, with most undecomposed organic residues remaining within
510 the POM fraction. Moreover, the residue-driven increases in both POM mass proportion and
511 organic carbon content under the CS treatment decreased over the incubation period, whereas
512 the corresponding values under the Bc treatment remained nearly constant. These findings
513 suggest that the quantity, quality, and incubation duration of organic residues are key factors
514 driving the increase in the POM mass proportion and organic carbon content. Additionally,
515 the extent of increase in the POM fraction was closely related to the amount and source of
516 organic material applied.

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

536 Currently, some studies have suggested that abundant POM can be crucial for
537 agroecosystem functioning and crop productivity, thereby advocating for greater research
538 focusing on POM increments (Wood et al., 2016). However, the results of this study

539 indicated that within the POM fraction, the dominant influencing factors were the quantity
540 and quality of undecomposed organic residues, with temporal factors exerting a significant
541 impact. Although the POM fraction plays an important role in nutrient supply, microbial
542 activity promotion, and soil structure regulation, the indiscriminate addition of organic
543 materials to soil primarily increases the amount of undecomposed organic residues, most of
544 which reside in the POM fraction over short time periods. This practice directly increases the
545 measured SOM content. However, most of the short-term increase originated from
546 undecomposed amendment residues retained in the POM fraction rather than from
547 microbially transformed and stabilized organic matter. These findings highlight the need to
548 distinguish between residue-derived and microbially transformed POM when interpreting
549 SOM measurements, particularly in short-term incubation studies. Without this distinction,
550 assessments of SOM dynamics may overestimate the short-term residue-driven increases in
551 POM. This could lead to misinterpretation of SOM stabilization and biased evaluation of
552 stable soil carbon pools in systems receiving recent organic amendments.

553

554 5. Conclusion

555 Based on the comprehensive results of this study, magnetic treatment exerted minimal
556 influence on the elemental composition of organic materials, indicating that magnetized
557 organic materials can serve as valid representatives of normal organic materials and that the
558 related experimental outcomes are reliable. The straw component in MCS decomposed
559 readily in soil, with its residue rate markedly decreasing during the incubation period. The
560 H/C ratio of the residues decreased, the O/C ratio increased, and both the C/N ratio and

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561 carbon concentration decreased continuously, indicating reduced aliphaticity, enhanced
562 oxidation, and a molecular structural shift toward increased aromaticity and enhanced
563 structural stability. Furthermore, the proportion of residues in the POM fraction sharply
564 declined with incubation time, approaching the characteristics of MAOM after 360 d. In
565 contrast, the biochar component in MBc exhibited high stability in soil, showing minor
566 changes in the residue rate, elemental ratios, and a relatively gradual decline in the proportion
567 of the POM fraction, reflecting greater resistance to decomposition. After organic material
568 input, increases in the operationally defined POM fraction are often interpreted as evidence of
569 SOM stabilization or formation of transformed organic matter. However, such increases may
570 simply result from recalcitrant and untransformed amendment residues. In this study, the
571 presence of unseparated residues in the CS and Bc treatments resulted in higher POM organic
572 carbon content and a greater proportion of total SOM than in CK. This effect was most
573 pronounced during the early incubation period. After residue separation, the MCS-D and
574 MBc-D treatments displayed little difference from CK, confirming that the observed POM
575 increases were attributable to incompletely decomposed residues. On day 30, the
576 residue-driven increases in POC content reached 63.48% and 58.99% for the CS and Bc
577 treatments, respectively. Over time, the residue-driven increase in CS gradually diminished,
578 decreasing to 15.34% after 360 d, whereas the residue-driven increase in Bc remained largely
579 unchanged and stable, still reaching 53.71% after 360 d. Owing to the greater conversion of
580 straw residues into MAOM during decomposition, the POM fraction contribution in MCS-D
581 was lower than that in CK. Concurrently, biochar in MBc-D exhibited no significant change,
582 with a POM contribution comparable to that of CK. These results confirm the risk of

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583 overestimating stabilized soil organic carbon pools when residue-derived POM is included in
584 the total SOM assessments. This risk is particularly evident in short-term incubation studies
585 or agroecosystems receiving recent organic amendments, where persistent recalcitrant
586 materials may bias the evaluation of SOM stability. These findings provide a useful reference
587 for the accurate evaluation of soil organic matter transformation processes and their content.

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

589
590 **CRedit authorship contribution statement :** Yuhan Xia: Writing – original draft,
591 Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation,
592 Conceptualization. Sen Dou: Writing – review & editing, Supervision, Resources, Project
593 administration, Methodology, Funding acquisition, Conceptualization. Guan Song: Writing –
594 review & editing, Supervision, Resources, Project administration, Methodology, Funding
595 acquisition, Conceptualization. Dilimulati Yalihong: Writing – review & editing,
596 Methodology, Investigation.

597
598 **Funding:** This work was supported by the National Key Research and Development Program
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600

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