

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

3 Yuhan Xia^a, Sen Dou^{a,*}, Song Guan^{a,*}, Dilimulati Yalihong^a

4 ^aKey Laboratory of Soil Resource Sustainable Utilization for Commodity Grain Bases of Jilin
5 Province, College of Resource and Environmental Science, Jilin Agricultural University,
6 Changchun 130118, China

7 18543718988@163.com (Y. Xia); 17843098635@163.com (D. Yalihong).

8 *Corresponding author.

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

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 exogenous organic residues from**
19 **indigenous SOM.** Consequently, increases in operationally defined POM are often
20 misinterpreted as evidence of SOM stabilization or microbially transformed organic carbon
21 formation. In this study, straw and biochar were magnetized through chemical coprecipitation
22 and applied to the soil. Magnetic separation was performed at successive incubation times to
23 isolate undegraded magnetic residues, thereby enabling more accurate tracking of SOM
24 dynamics. Five treatments were established: blank control (CK), untreated straw (CS),
25 untreated biochar with carbon input equivalent to straw (Bc), magnetized straw (MCS), and
26 magnetized biochar (MBc). The recovery of magnetized straw residues declined continuously
27 and reached 54.55% after 360 d, whereas biochar residues remained highly persistent at
28 92.48%. In the CS and Bc treatments, the organic carbon content of POM fractions and their
29 proportion in total SOM were consistently higher than in CK, particularly during early
30 incubation. **However, after removing undegraded residues by magnetic separation, values**
31 **were close to those of CK.** This result indicates that the observed POM increases mainly
32 originated from undecomposed external residues rather than microbially stabilized SOM. On

33 day 30, the apparent increase in particulate organic carbon (POC) was 63.48% in CS and
34 58.99% in Bc. Over time, the apparent POC increase in CS declined to 15.34% by day 360,
35 whereas that in Bc remained high (53.71%). These findings suggest that interpreting total
36 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

42 1. Introduction

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

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 transient and
67 non-stabilized, as POM remains susceptible to decomposition and transformation even under
68 the physical protection of soil (Connell et al., 2025), and such short-term increases exhibit
69 low persistence in soil (Janzen, 2015; Powlson et al., 2014). Currently, an accurate
70 assessment of the proportion and duration of this transient and non-stabilized, residue-derived
71 increase in POM mass and organic carbon content at various times following organic material
72 application is still lacking.

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

86 facilitate the combined application of organic materials in soil. Iron particles form stable
87 chemical bonds with organic materials, rather than simple physical adsorption. The surfaces
88 of these materials contain abundant oxygen-containing functional groups such as hydroxyl,
89 carboxyl, and carbonyl groups. During coprecipitation, these groups react with Fe^{2+} and Fe^{3+}
90 to form coordinated and covalent bonds (Zhou et al., 2019; Duan et al., 2022). The resulting
91 magnetic nanoparticles are uniformly embedded within the porous structure of the organic
92 materials. This embedding prevents their detachment under non-biodegradation conditions,
93 such as physical disturbance or soil hydration. When soil microorganisms decompose organic
94 components, including cellulose, hemicellulose, and lignin, the functional groups that bind
95 iron particles are disrupted. As a result, magnetic nanoparticles detach or disperse into
96 non-magnetic fine particles smaller than 10 nm, which cannot be captured by magnetic fields.
97 Consequently, decomposed residues completely lose their magnetism (Li et al., 2024).

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

108

109 **2. Materials and Methods**

110 *2.1. Experimental materials*

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

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

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

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

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

146

147 *2.2. Experimental Design*

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

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

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

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

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

174 a 2 mm mesh for subsequent analyses.

175

176 2.3. Fractionation of POM and MAOM

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

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

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

$$203 \quad POC = M_p / 100 \times OC_p \quad (1)$$

$$204 \quad POM - C \text{ Contribution (\%)} = POC / SOC \times 100 \quad (2)$$

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

211

212 2.4. Calculation of organic residue retention rate

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

$$215 \quad L(\%) = \frac{M_d - M_{Fe}}{M_1} \times 100\% \quad (3)$$

216 where L is the mass retention rate of the organic residue (%), M_d is the dry mass of the
217 recovered magnetized material at different decomposition times (g), M_{Fe} is the dry mass of

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

222

223 *2.5. Data analysis*

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

233

234 **3. Results and analysis**

235 *3.1. Differences between magnetized and original organic materials*

236 As shown in Table 1, no significant differences were observed in the molar ratios of
237 carbon to nitrogen (C/N), hydrogen to carbon (H/C), or oxygen to carbon (O/C) before and
238 after magnetic modification of the organic materials. This result indicates that the
239 magnetization process does not substantially alter the elemental composition of organic

240 materials. The C/N, H/C, and O/C ratios serve as key indicators of the chemical properties
241 and structural characteristics of organic materials. Specifically, the C/N ratio could be closely
242 associated with the decomposition rate of organic substrates, the H/C ratio reflects
243 aromaticity, and the O/C ratio represents the oxidation level (Ndzelu et al., 2021). The
244 near-constant values of these ratios before and after magnetization suggest that the
245 fundamental chemical attributes and structural features of the organic materials remained
246 unchanged by magnetic treatment.

247 The metallic nanoparticles produced by coprecipitation were uniformly distributed on
248 the surfaces of straw and biochar within a narrow size range. They formed a discontinuous
249 and porous coating, rather than a dense and impermeable layer. This nanoscale coating does
250 not block surface functional groups or internal pore structures, thereby preserving the natural
251 accessibility of organic materials to soil microorganisms (Panda et al., 2026). As a result, the
252 decomposition behavior of the magnetized materials remained consistent with that of the
253 unmodified materials, supporting their reliability in tracking SOM transformation processes.
254 Therefore, the magnetized organic materials exhibited high chemical and structural
255 consistency with their non-magnetized counterparts, making them reliable representatives of
256 original organic substrates. This conclusion could present a sound theoretical basis for using
257 magnetized organic materials in subsequent experiments to investigate the behavior of
258 undecomposed organic residues in soil. It also ensured the reliability and accuracy of results
259 related to the assessment of residue-driven increases in soil organic matter through the
260 separation of magnetized organic residues.

261

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

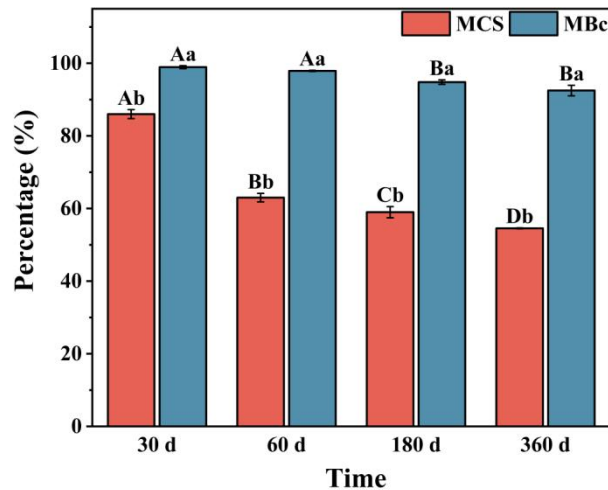
| Treatment | N | C | H | O | C/N | H/C | O/C |
|-----------|------|-------|------|-------|--------|-------|-------|
| | % | | | | Ratio | Ratio | Ratio |
| CS | 0.99 | 46.20 | 6.84 | 45.96 | 54.32 | 1.78 | 0.75 |
| Bc | 0.78 | 79.35 | 3.65 | 16.22 | 118.49 | 0.55 | 0.15 |
| MCS | 1.00 | 46.68 | 6.55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

264

265 *3.2. Temporal changes in magnetized organic residues in soil*

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

276



277

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

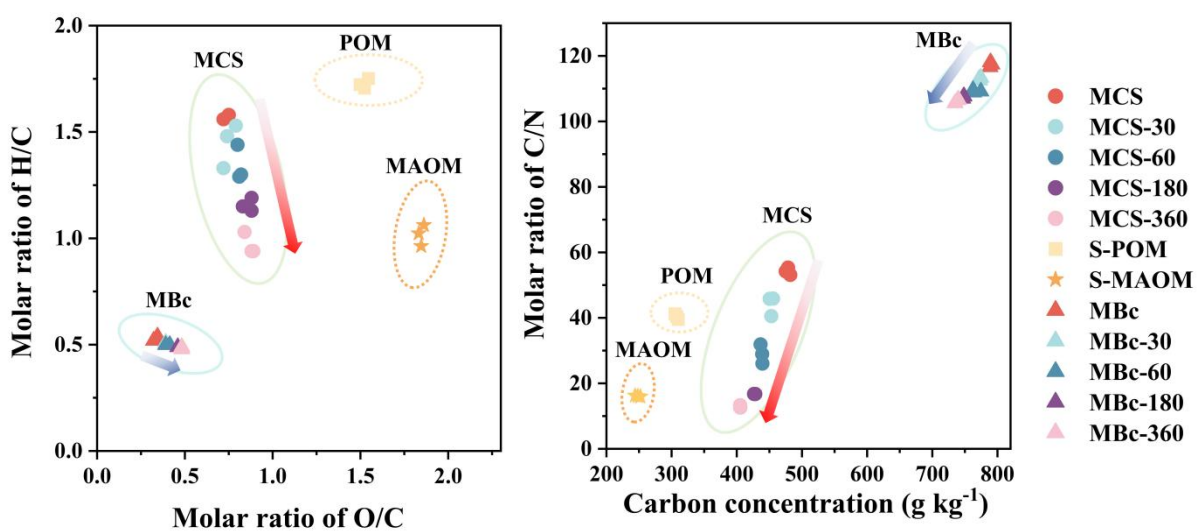
280 Note: MCS refers to magnetized straw; MBc refers to magnetized biochar. Different
 281 uppercase letters indicate significant differences among sampling times within the same
 282 organic residue ($p < 0.05$), while different lowercase letters indicate significant differences
 283 between organic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

284

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

294 (Mohammed et al., 2023). These findings indicate that with prolonged incubation, shifts in
 295 the H/C and O/C ratios of the organic residues (evident from the bulk elemental analysis
 296 presented in Fig. 2) are consistent with oxidative transformation and changes in aliphatic
 297 content and structural condensation of the organic material. Fig. 2b further shows that the
 298 C/N ratio and carbon concentration of MCS residues declined continuously, gradually
 299 approaching those of the soil MAOM fraction. This trend reflects the progressive
 300 decomposition and transformation of organic residues toward chemical characteristics similar
 301 to those of native soil mineral-associated organic matter, consistent with observations of
 302 organic matter stabilization in previous studies (Abakumov and Eskov, 2023). Notably, the
 303 C/N ratio of MCS residues at 360 d approximated that of MAOM. Conversely, the changes in
 304 these parameters for MBc residues were relatively small, indicating that the organic
 305 components of MBc residues were more resistant to microbial decomposition and
 306 transformation than straw residues within the 360-day incubation period.

307



308

309 **Fig. 2.** Van Krevelen diagram of atomic H/C and O/C ratios (a), and comparison of C/N ratio
 310 and carbon concentration (b) of magnetized organic residues, soil POM, and MAOM

311 fractions at different incubation times.

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

319

320 *3.3. Organic residues cause residue-derived increases in the mass proportion and organic* 321 *carbon content of soil POM fraction*

322 Fig. 3 presents the relative mass proportions of the soil POM fraction at different
323 incubation times across treatments. Clear differences among treatments were evident.
324 Two-way ANOVA (Table S1) revealed that the relative mass proportion of the POM fraction
325 (M_P) was significantly affected by treatment ($p < 0.001$) and incubation time ($p < 0.01$), with no
326 significant interaction between treatment and time ($p > 0.05$). Similarly, as shown in Fig.3, the
327 organic carbon content of the POM fraction (OC_P) was significantly influenced by treatment
328 ($p < 0.001$), incubation time ($p < 0.001$), and their interaction ($p < 0.001$). Notably, no significant
329 differences were observed between the MCS-O and MBc-O (magnetized treatments without
330 removing magnetic organic residues at harvest) and the CS and Bc treatments at any
331 sampling time, supporting the applicability of magnetized materials in soil applications.

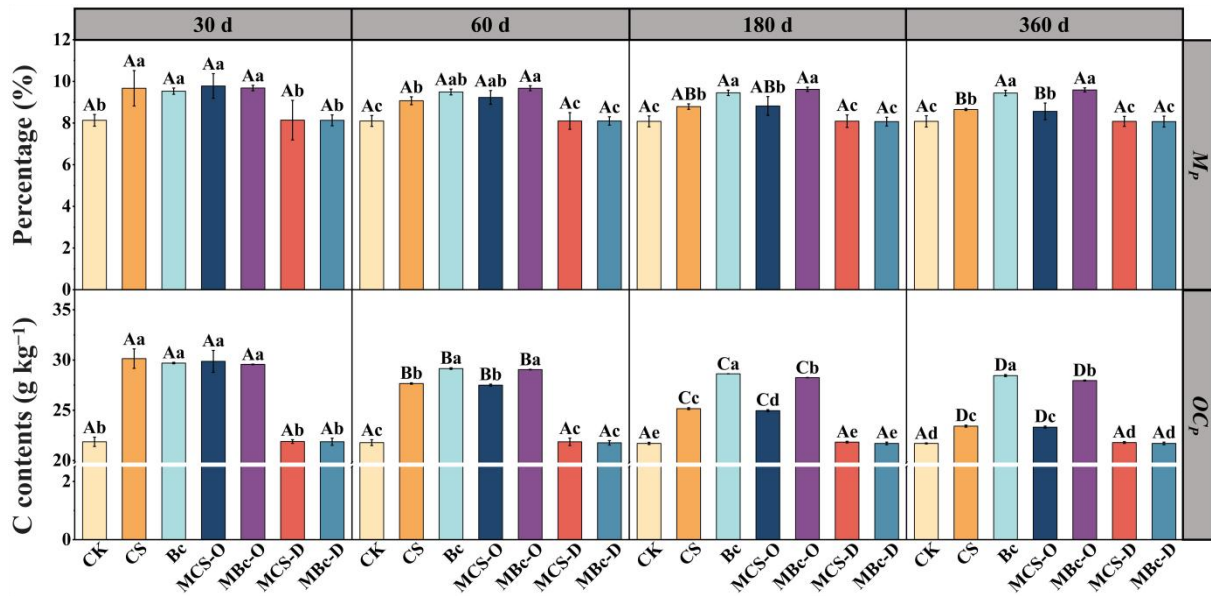
332 At 30, 60, 180, and 360 d of incubation, the mass proportion of the POM fraction (MP)

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

344 Similarly, at different time points, the organic carbon content of the POM fraction (OC_P)
345 in the CS treatment increased by 37.87%, 26.99%, 15.94%, and 7.92%, respectively,
346 compared with CK. For the Bc treatment, the increases were 35.86%, 33.83%, 31.93%, and
347 31.10%, respectively. At the same time points, the OC_P in the CS treatment exceeded that in
348 the MCS-D treatment by 37.68%, 26.53%, 15.25%, and 7.48%, respectively. Moreover, the
349 OC_P in the Bc treatment was higher than in the MBc-D treatment by 35.80%, 33.96%,
350 31.93%, and 31.10%. These results demonstrated that both the carbon content and mass
351 proportion of the POM fraction exhibited residue-driven increases, resulting from the
352 retention of persistent amendment residues within the operationally defined $>53 \mu\text{m}$
353 particulate fraction. As no significant difference was identified between the MCS-D and CK
354 treatments, the reduction in the residue-derived increase for the CS treatment was attributable

355 not to an increase in organic carbon content in the MCS-D treatment but to the decomposition
 356 of organic residues within the fraction.

357



358

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

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

371

372 **3.4. Organic residues cause residue-derived increases in POC and SOC contents**

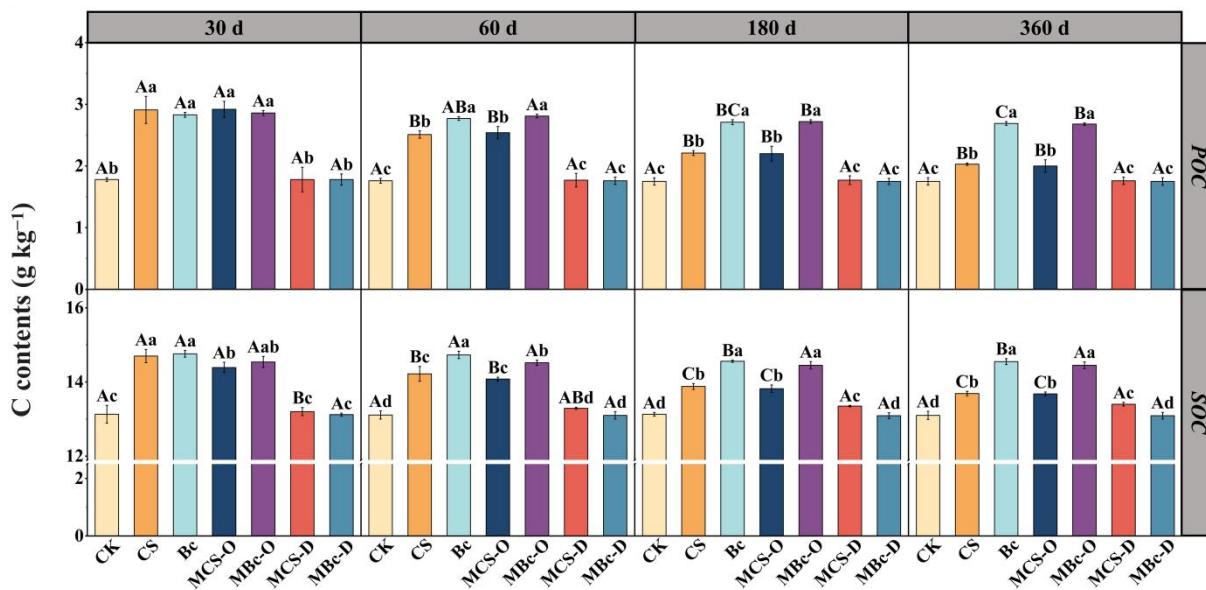
373 As shown in Fig. 4 and Table S2, two-way ANOVA indicated that the POC content was
374 significantly affected by treatment ($p < 0.001$), incubation time ($p < 0.001$), and their interaction
375 ($P < 0.001$). Similarly, the SOC content was significantly influenced by treatment ($p < 0.001$),
376 incubation time ($p < 0.001$), and their interaction ($p < 0.001$). The POC contents in the MCS-O
377 and MBc-O treatments were slightly lower than those in the CS and Bc treatments, although
378 the differences were not statistically significant. Specifically, at 30, 60, 180, and 360 d of
379 incubation, the POC contents in both the CS and Bc treatments were significantly higher than
380 those in CK. The increase in POC content compared with CK in the CS treatment showed a
381 clear decreasing trend, with increases of 63.48%, 42.61%, 26.29%, and 16.00%, respectively.

382 **In contrast, although the POC content in the Bc treatment also declined during incubation, the**
383 **decrease was less pronounced, with increases of 58.99%, 57.38%, 54.86%, and 53.71% at the**
384 **respective time points.** No significant differences in POC content were observed between the

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

390 Across all incubation periods, the SOC contents in the MCS-O and MBc-O treatments
391 were comparable to those in the CS and Bc treatments, indicating strong consistency between
392 the magnetized organic materials and the original organic materials during incubation.

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



403
 404 **Fig. 4.** *POC* and *SOC* contents of different treatments at various incubation times.

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

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

415

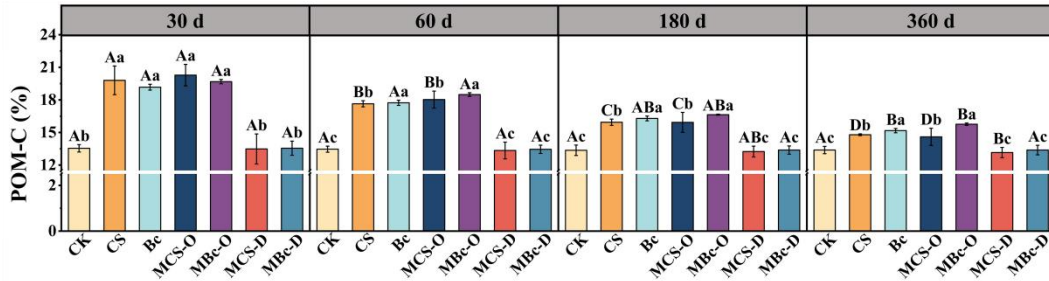
416 *3.5. Organic residues cause residue-derived increases in the proportion of POM in total* 417 *SOM*

418 As shown in Fig. 5 and Table S3, two-way ANOVA revealed that the contribution of
419 POC to total SOC (POM-C contribution, POC/SOC) was significantly affected by treatment
420 ($p < 0.001$), incubation time ($p < 0.001$), and their interaction ($p < 0.001$). POM-C in the CS and
421 Bc treatments was significantly higher than that in CK. At different incubation times, the
422 ratios in the CS treatment increased by 46.23%, 31.05%, 19.31%, and 10.54%, whereas those
423 in the Bc treatment increased by 41.58%, 39.60%, 39.15%, and 38.04%, respectively.

424 *However, the residue-driven elevation of the POM proportion in SOM persisted.* At different
425 time points, the ratios in the CS treatment were 46.88%, 32.23%, 20.39%, and 12.47% higher
426 than those in the MCS-D treatment, whereas in the Bc treatment, they were 41.47%, 39.70%,
427 38.94%, and 38.04% higher than those in the MBc-D treatment. Notably, the POM
428 proportion in SOM in the MCS-D treatment was lower than that in CK, which was attributed
429 to the greater conversion of straw residues into MAOM during decomposition, thereby
430 increasing the MAOM proportion in SOM. In contrast, no significant changes were observed

431 in biochar in the MBc-D treatment, and the proportion of POM in SOM was similar to that in
 432 CK.

433



434

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

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

447

448 4. Discussion

449 4.1. Differences in the transformation of organic materials with different qualities in soil

450 As shown in Fig. 1, the proportion of undecomposed straw residues significantly

451 decreased over different incubation periods, with a residue rate of only 54.55% after 360 d. In
452 sharp contrast, biochar exhibited almost no decomposition, maintaining a high residue rate of
453 92.48%. Based on the bulk elemental analysis in Fig. 2, the organic straw component within
454 magnetic straw residues underwent progressive oxidative transformation and structural
455 condensation with incubation time, as reflected by the gradual shifts in H/C and O/C ratios,
456 indicating a gradual evolution toward more chemically stable characteristics. Meanwhile, the
457 magnetic mineral phase remained preserved, resulting in the persistent magnetic properties of
458 the residual materials. By contrast, MBc residues exhibited negligible changes in elemental
459 composition throughout the incubation period.

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

473 The high stability of biochar observed in this study confirms its unique advantages as a
474 carbon-rich soil amendment for soil carbon sequestration and structural improvement, which
475 is consistent with previous studies (Cao et al., 2022; Fan et al., 2021; Wang et al., 2025;
476 Zhang et al., 2024). Characterized by slow decomposition and a surface conducive to organic
477 molecule aggregation, biochar can effectively reduce soil bulk density (Zhang et al., 2021),
478 increase soil porosity (He et al., 2022), alleviate soil acidification (Shi et al., 2023), retain soil
479 moisture (Khaledi et al., 2023), and enhance nutrient absorption efficiency and nutrient
480 cycling coordination (Burgeon et al., 2022) when applied to soil. Therefore, despite its slow
481 decomposition in soil, biochar plays a significant role in improving soil structure and function,
482 which is further supported by its high persistence observed in the present one-year incubation
483 experiment.

484 *4.2. Residual undecomposed organic matter contributes to increases in the POM fraction*

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

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

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

517 organic material applied.

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

538 Currently, some studies have suggested that abundant POM can be crucial for

539 agroecosystem functioning and crop productivity, thereby advocating for greater research
540 focusing on POM increments (Wood et al., 2016). However, the results of this study
541 indicated that within the POM fraction, the dominant influencing factors were the quantity
542 and quality of undecomposed organic residues, with temporal factors exerting a significant
543 impact. Although the POM fraction plays an important role in nutrient supply, microbial
544 activity promotion, and soil structure regulation, the indiscriminate addition of organic
545 materials to soil primarily increases the amount of undecomposed organic residues, most of
546 which reside in the POM fraction over short time periods. This practice directly increases the
547 measured SOM content. **Notably, the observed short-term increase in soil organic carbon was
548 primarily derived from undecomposed exogenous organic residues retained in the particulate
549 organic matter (POM) fraction, rather than the formation of microbially processed and
550 mineral-associated stable organic matter pools. These findings highlight the need to
551 distinguish between residue-derived POM and microbially transformed MAOM when
552 interpreting SOM measurements, particularly in short-term incubation studies.** Without this
553 distinction, assessments of SOM dynamics may overestimate the short-term residue-driven
554 increases in POM. This could lead to misinterpretation of SOM stabilization and biased
555 evaluation of stable soil carbon pools in systems receiving recent organic amendments.

556

557 **5. Conclusion**

558 Based on the comprehensive results of this study, magnetic treatment exerted minimal
559 influence on the elemental composition of organic materials, indicating that magnetized
560 organic materials can serve as valid representatives of normal organic materials and that the

561 related experimental outcomes are reliable. The straw component in MCS decomposed
562 readily in soil, with its residue rate markedly decreasing during the incubation period. The
563 H/C ratio of the residues decreased, the O/C ratio increased, and both the C/N ratio and
564 carbon concentration decreased continuously, indicating reduced aliphaticity, enhanced
565 oxidation, and a molecular structural shift toward increased aromaticity and enhanced
566 structural stability. Furthermore, the proportion of residues in the POM fraction sharply
567 declined with incubation time, approaching the characteristics of MAOM after 360 d. In
568 contrast, the biochar component in MBc exhibited high stability in soil, showing minor
569 changes in the residue rate, elemental ratios, and a relatively gradual decline in the proportion
570 of the POM fraction, reflecting greater resistance to decomposition. After organic material
571 addition, the accumulation of the operationally defined POM fraction is frequently regarded
572 as an indicator of enhanced soil organic carbon sequestration or microbially mediated organic
573 matter transformation. However, as a labile organic pool, the elevated POM observed in this
574 study was largely derived from recalcitrant and untransformed exogenous amendment
575 residues, rather than the formation of chemically stable soil organic matter. In this study, the
576 presence of unseparated residues in the CS and Bc treatments resulted in higher POM organic
577 carbon content and a greater proportion of total SOM than in CK. This effect was most
578 pronounced during the early incubation period. After residue separation, the MCS-D and
579 MBc-D treatments displayed little difference from CK, confirming that the observed POM
580 increases were attributable to incompletely decomposed residues. On day 30, the
581 residue-driven increases in POC content reached 63.48% and 58.99% for the CS and Bc
582 treatments, respectively. Over time, the residue-driven increase in CS gradually diminished,

583 decreasing to 15.34% after 360 d, whereas the residue-driven increase in Bc remained largely
584 unchanged and stable, still reaching 53.71% after 360 d. Owing to the greater conversion of
585 straw residues into MAOM during decomposition, the POM fraction contribution in MCS-D
586 was lower than that in CK. Concurrently, biochar in MBc-D exhibited no significant change,
587 with a POM contribution comparable to that of CK. These results confirm the risk of
588 overestimating stabilized soil organic carbon pools when residue-derived POM is included in
589 the total SOM assessments. This risk is particularly evident in short-term incubation studies
590 or agroecosystems receiving recent organic amendments, especially when incorporating
591 pyrogenic carbon such as biochar. As a notable exception to the general lability of POM,
592 such persistent recalcitrant materials can lead to an overestimation of soil organic matter
593 stability, as their persistence arises from inherent chemical recalcitrance rather than
594 microbially mediated stabilization processes. These findings provide a useful reference for
595 the accurate evaluation of soil organic matter transformation processes and their content.

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

597

598 **CRedit authorship contribution statement :** Yuhan Xia: Writing – original draft,
599 Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation,
600 Conceptualization. Sen Dou: Writing – review & editing, Supervision, Resources, Project
601 administration, Methodology, Funding acquisition, Conceptualization. Guan Song: Writing –
602 review & editing, Supervision, Resources, Project administration, Methodology, Funding
603 acquisition, Conceptualization. Dilimulati Yalihong: Writing – review & editing,
604 Methodology, Investigation.

605

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

608

609 **References**

610 Abakumov, E., Eskov, A., 2023. Organic matter structural composition of vascular epiphytic
611 suspended soils of South Vietnam. *Applied Sciences* 13, 4473.
612 <https://doi.org/10.3390/app13074473>.

613 Angst, G., Mueller, K.E., Nierop, K.G.J., Simpson, M.J., 2021. Plant- or microbial-derived?
614 A review on the molecular composition of stabilized soil organic matter. *Soil Biology
615 and Biochemistry* 156, 108189. <https://doi.org/10.1016/j.soilbio.2021.108189>.

616 Arumugam, T., Kinattinkara, S., Vellingiri, K., Arumugam, M., Rajamani, J., Jayaseelan, A.,
617 2025. Assessment of agricultural soil quality in macro and micronutrient analysis of
618 Kasargod, Kerala, India, using GIS techniques. *J. Hazard. Mater. Adv.* 19, 100846.
619 <https://doi.org/10.1016/j.hazadv.2025.100846>

620 Banach-Szott, M., Debska, B., Rosa, E., 2014. Effect of soil pollution with polycyclic
621 aromatic hydrocarbons on the properties of humic acids. *Journal of Soils and Sediments*
622 14, 1169–1178. <https://doi.org/10.1007/s11368-014-0873-9>.

623 Baragaño, D., Alonso, J., Gallego, J.R., Lobo, M.C., Gil-Díaz, M., 2020. Magnetite
624 nanoparticles for the remediation of soils co-contaminated with As and PAHs. *Chemical
625 Engineering Journal* 399, 125809. <https://doi.org/10.1016/j.cej.2020.125809>.

626 Bhattacharyya, R., Kundu, S., Srivastva, A.K., Gupta, H.S., Prakash, V., Bhatt, J.C., 2011.
627 Long term fertilization effects on soil organic carbon pools in a sandy loam soil of the

628 Indian sub-Himalayas. Plant and Soil 341, 109–124.
629 <https://doi.org/10.1007/s11104-010-0627-4>.

630 Bornø, M.L., Müller-Stöver, D.S., Liu, F.L., 2019. Biochar properties and soil type drive the
631 uptake of macro- and micronutrients in maize (*Zea mays* L.). Journal of Plant Nutrition
632 and Soil Science 182, 149–158. <https://doi.org/10.1002/jpln.201800228>.

633 Brown, K.H., Bach, E.M., Drijber, R.A., Hofmockel, K.S., Jeske, E.S., Sawyer, J.E.,
634 Castellano, M.J., 2014. A long-term nitrogen fertilizer gradient has little effect on soil
635 organic matter in a high-intensity maize production system. Global Change Biology 20,
636 1339–1350. <https://doi.org/10.1111/gcb.12519>.

637 Burgeon, V., Fouché, J., Garré, S., Dehkordi, R.H., Colinet, G., Cornelis, J.T., 2022. Young
638 and century-old biochars strongly affect nutrient cycling in a temperate agroecosystem.
639 Agriculture, Ecosystems & Environment 328, 107847.
640 <https://doi.org/10.1016/j.agee.2021.107847>.

641 Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic-matter changes across a
642 grassland cultivation sequence. Soil Science Society of America Journal 56, 777–783.
643 <https://doi.org/10.2136/sssaj1992.03615995005600030017x>.

644 Cao, L.Y., Zhang, X.Y., Xu, Y., Xiang, W., Wang, R., Ding, F.J., Hong, P.Z., Gao, B., 2022.
645 Straw and wood based biochar for CO₂ capture: Adsorption performance and governing
646 mechanisms. Separation and Purification Technology 287, 120592.
647 <https://doi.org/10.1016/j.seppur.2022.120592>.

648 Castellano, M.J., Mueller, K.E., Olk, D.C., Sawyer, J.E., Six, J., 2015. Integrating plant litter
649 quality, soil organic matter stabilization, and the carbon saturation concept. Global

650 Change Biology 21, 3200–3209. <https://doi.org/10.1111/gcb.12982>.

651 Chen, H.L., Zhou, J.M., Xiao, B.H., 2010. Characterization of dissolved organic matter
652 derived from rice straw at different stages of decay. *Journal of Soils and Sediments* 10,
653 915–922. <https://doi.org/10.1007/s11368-010-0210-x>.

654 Chen, L.M., Sun, S.L., Zhou, Y.Y., Zhang, B.X., Peng, Y.T., Zhuo, Y.C., Ai, W.K., Gao, C.F.,
655 Wu, B., Liu, D.W., Sun, C.R., 2023. Straw and straw biochar differently affect fractions
656 of soil organic carbon and microorganisms in farmland soil under different water
657 regimes. *Environmental Technology & Innovation* 32, 103412.
658 <https://doi.org/10.1016/j.eti.2023.103412>.

659 Christensen, B.T., 1992. Physical fractionation of soil and organic matter in primary particle
660 size and density separates. In: Stewart, B.A. (Ed.), *Advances in Soil Science*. Springer
661 New York, New York, NY, pp. 1–90. https://doi.org/10.1007/978-1-4612-2930-8_1.

662 Connell, R.K., James, T.Y., Blesh, J., 2025. A legume-grass cover crop builds
663 mineral-associated organic matter across variable agricultural soils. *Soil Biology and*
664 *Biochemistry* 203, 109726. <https://doi.org/10.1016/j.soilbio.2025.109726>.

665 Cotrufo, M.F., Haddix, M.L., Kroeger, M.E., Stewart, C.E., 2022. The role of plant input
666 physical-chemical properties, and microbial and soil chemical diversity on the formation
667 of particulate and mineral-associated organic matter. *Soil Biology and Biochemistry* 168,
668 108648. <https://doi.org/10.1016/j.soilbio.2022.108648>.

669 Cotrufo, M.F., Soong, J.L., Horton, A.J., Campbell, E.E., Haddix, M.L., Wall, D.H., Parton,
670 W.J., 2015. Formation of soil organic matter via biochemical and physical pathways of
671 litter mass loss. *Nature Geoscience* 8, 776–779. <https://doi.org/10.1038/ngeo2520>.

672 Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, E., 2013. The Microbial
673 Efficiency- Matrix Stabilization (MEMS) framework integrates plant litter
674 decomposition with soil organic matter stabilization: Do labile plant inputs form stable
675 soil organic matter? *Global Change Biology* 19, 988–995.
676 <https://doi.org/10.1111/gcb.12113>.

677 Dou, S., Li, K., 2010. Effect of organic matter application on CP-MAS-13C-NMR spectra of
678 humic acids from a brown soil. In: Xu, J.M., Huang, P.M. (Eds.), *Molecular
679 Environmental Soil Science at the Interfaces in the Earth's Critical Zone*. Springer
680 Berlin Heidelberg, Berlin, Heidelberg, pp. 29–31.
681 https://doi.org/10.1007/978-3-642-05297-2_9.

682 Dou, S., Shan, J., Song, X.Y., Cao, R., Wu, M., Li, C.L., Guan, S., 2020. Are humic
683 substances soil microbial residues or unique synthesized compounds? A perspective on
684 their distinctiveness. *Pedosphere* 30, 159–167.
685 [https://doi.org/10.1016/S1002-0160\(20\)60001-7](https://doi.org/10.1016/S1002-0160(20)60001-7).

686 Duan, L.C., Wang, Q.H., Li, J.N., Wang, F.H., Yang, H., Guo, B.L., Hashimoto, Y., 2022.
687 Zero valent iron or Fe₃O₄-loaded biochar for remediation of Pb contaminated sandy soil:
688 Sequential extraction, magnetic separation, XAFS and ryegrass growth. *Environmental
689 Pollution* 308, 119702. <https://doi.org/10.1016/j.envpol.2022.119702>.

690 Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter
691 turnover is governed by accessibility not recalcitrance. *Global Change Biology* 18,
692 1781–1796. <https://doi.org/10.1111/j.1365-2486.2012.02665.x>.

693 Fan, Y.V., Klemes, J.J., Lee, C.T., 2021. Environmental performance and techno-economic

694 feasibility of different biochar applications: An overview. *Chemical Engineering*
695 *Transactions* 83, 469–474. <https://doi.org/10.3303/CET2183079>.

696 Feng, H.L., Han, X.Z., Biswas, A., Zhang, M., Zhu, Y.C., Ji, Y.X., Lu, X.C., Chen, X., Yan, J.,
697 Zou, W.X., 2025. Long-term organic material application enhances black soil
698 productivity by improving aggregate stability and dissolved organic matter dynamics.
699 *Field Crops Research* 328, 109946. <https://doi.org/10.1016/j.fcr.2025.109946>.

700 Guo, X.W., Viscarra Rossel, R.A., Wang, G.C., Xiao, L.J., Wang, M.M., Zhang, S., Luo, Z.K.,
701 2022. Particulate and mineral-associated organic carbon turnover revealed by modelling
702 their long-term dynamics. *Soil Biology and Biochemistry* 173, 108780.
703 <https://doi.org/10.1016/j.soilbio.2022.108780>.

704 He, W., Wang, H., Ye, W.H., Tian, Y.L., Hu, G.Q., Lou, Y.H., Pan, H., Yang, Q.G., Zhuge, Y.P.,
705 2022. Distinct stabilization characteristics of organic carbon in coastal salt-affected soils
706 with different salinity under straw return management. *Land Degradation &*
707 *Development* 33, 2246–2257. <https://doi.org/10.1002/ldr.4276>.

708 Hua, F.Y., Bruijnzeel, L.A., Meli, P., Martin, P.A., Zhang, J., Nakagawa, S., Miao, X., Wang,
709 W., McEvoy, C., Peña-Arancibia, J.L., Brancalion, P.H.S., Smith, P., Edwards, D.P.,
710 Balmford, A., 2022. The biodiversity and ecosystem service contributions and trade-offs
711 of forest restoration approaches. *Science* 376, 839–844.
712 <https://doi.org/10.1126/science.abl4649>.

713 Janzen, H.H., 2015. Beyond carbon sequestration: soil as conduit of solar energy. *European J*
714 *Soil Science* 66, 19–32. <https://doi.org/10.1111/ejss.12194>.

715 Khaledi, S., Delbari, M., Galavi, H., Bagheri, H., Chari, M.M., 2023. Effects of biochar

716 particle size, biochar application rate, and moisture content on thermal properties of an
717 unsaturated sandy loam soil. *Soil and Tillage Research* 226, 105579.
718 <https://doi.org/10.1016/j.still.2022.105579>.

719 Kleber, M., Sollins, P., Sutton, R., 2007. A conceptual model of organo-mineral interactions
720 in soils: Self-assembly of organic molecular fragments into zonal structures on mineral
721 surfaces. *Biogeochemistry* 85, 9–24. <https://doi.org/10.1007/s10533-007-9103-5>.

722 Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2020. Conceptualizing soil organic matter into
723 particulate and mineral-associated forms to address global change in the 21st century.
724 *Global Change Biology* 26, 261–273. <https://doi.org/10.1111/gcb.14859>.

725 Li, X.N., Li, R.P., Zhan, M.Q., Hou, Q., Zhang, H.Y., Wu, G.Q., Ding, L.Q., Lv, X.F., Xu, Y.,
726 2024. Combined magnetic biochar and ryegrass enhanced the remediation effect of soils
727 contaminated with multiple heavy metals. *Environment International* 185, 108498.
728 <https://doi.org/10.1016/j.envint.2024.108498>.

729 Liang, J.J., Crowther, T.W., Picard, N., Wiser, S., Zhou, M., Alberti, G., Schulze, E.D.,
730 McGuire, A.D., Bozzato, F., Pretzsch, H., de-Miguel, S., Paquette, A., Hérault, B.,
731 Scherer-Lorenzen, M., Barrett, C.B., Glick, H.B., Hengeveld, G.M., Nabuurs, G.J.,
732 Pfautsch, S., Viana, H., Vibrans, A.C., Ammer, C., Schall, P., Verbyla, D., Tchebakova,
733 N., Fischer, M., Watson, J.V., Chen, H.Y.H., Lei, X., Schelhaas, M.J., Lu, H., Gianelle,
734 D., Parfenova, E.I., Salas, C., Lee, E., Lee, B., Kim, H.S., Bruelheide, H., Coomes, D.A.,
735 Piotto, D., Sunderland, T., Schmid, B., Gourlet-Fleury, S., Sonké, B., Tavani, R., Zhu, J.,
736 Brandl, S., Vayreda, J., Kitahara, F., Searle, E.B., Neldner, V.J., Ngugi, M.R., Baraloto,
737 C., Frizzera, L., Bałazy, R., Oleksyn, J., Zawila-Niedźwiecki, T., Bouriaud, O., Bussotti,

738 F., Finér, L., Jaroszewicz, B., Jucker, T., Valladares, F., Jagodzinski, A.M., Peri, P.L.,
739 Gonmadje, C., Marthy, W., O'Brien, T., Martin, E.H., Marshall, A.R., Rovero, F.,
740 Bitariho, R., Niklaus, P.A., Alvarez-Loayza, P., Chamuya, N., Valencia, R., Mortier, F.,
741 Wortel, V., Engone-Obiang, N.L., Ferreira, L.V., Odeke, D.E., Vasquez, R.M., Lewis,
742 S.L., Reich, P.B., 2016. Positive biodiversity-productivity relationship predominant in
743 global forests. *Science* 354, aaf8957. <https://doi.org/10.1126/science.aaf8957>.

744 Liu, J.X., Sun, P., Chen, Y.Y., Guo, J.M., Liu, L.C., Zhao, X.Y., Xin, J., Liu, X.L., 2024. The
745 regulation pathways of biochar and microorganism in soil-plant system by multiple
746 statistical methods: The forms of carbon participation in coastal wetlands. *Chemosphere*
747 362, 142918. <https://doi.org/10.1016/j.chemosphere.2024.142918>.

748 Mitchell, E., Scheer, C., Rowlings, D., Conant, R.T., Cotrufo, M.F., Grace, P., 2018. Amount
749 and incorporation of plant residue inputs modify residue stabilisation dynamics in soil
750 organic matter fractions. *Agriculture, Ecosystems & Environment* 256, 82–91.
751 <https://doi.org/10.1016/j.agee.2017.12.006>.

752 Mohammed, I., Kodaolu, B., Zhang, T.Q., Wang, Y.T., Audette, Y., Longstaffe, J., 2023.
753 Analysis of molecular structure changes in humic acids from manure-amended soils
754 over 17 years using elemental analysis and solid-state ¹³C nuclear magnetic resonance
755 spectroscopy. *Soil Systems* 7, 76. <https://doi.org/10.3390/soilsystems7030076>.

756 Ndzelu, B.S., Dou, S., Zhang, X.W., Zhang, Y.F., Ma, R., Liu, X., 2021. Tillage effects on
757 humus composition and humic acid structural characteristics in soil aggregate-size
758 fractions. *Soil and Tillage Research* 213, 105090.
759 <https://doi.org/10.1016/j.still.2021.105090>.

760 Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In:
761 Page, A.L. (Ed.), *Methods of Soil Analysis: Part 2 Chemical and Microbiological*
762 *Properties*. Wiley, Hoboken, pp. 539–579.
763 <https://doi.org/10.2134/agronmonogr9.2.2ed.c29>.

764 Panda, S., Devi, N., Maiti, P., Chatterjee, A., Hazra P., Singh, V., Parmar, P., Meikap, B., 2026.
765 Development of a novel FeCl₃-activated magnetic biochar for adsorptive removal of
766 paracetamol and environmental impact analysis. *Powder Technology* 470, 122021.
767 <https://doi.org/10.1016/j.powtec.2025.122021>.

768 Papageorgiou, A., Azzi, E.S., Enell, A., Sundberg, C., 2021. Biochar produced from wood
769 waste for soil remediation in Sweden: Carbon sequestration and other environmental
770 impacts. *Science of The Total Environment* 776, 145953.
771 <https://doi.org/10.1016/j.scitotenv.2021.145953>.

772 Pathy, A., Pokharel, P., Chen, X.L., Balasubramanian, P., Chang, S.X., 2023. Activation
773 methods increase biochar's potential for heavy-metal adsorption and environmental
774 remediation: A global meta-analysis. *Science of The Total Environment* 865, 161252.
775 <https://doi.org/10.1016/j.scitotenv.2022.161252>.

776 Powelson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman,
777 K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature*
778 *Climate Change* 4, 678–683. <https://doi.org/10.1038/nclimate2292>.

779 Rana, P., Soni, V., Sharma, S., Poonia, K., Patial, S., Singh, P., Selvasembian, R., Chaudhary,
780 V., Hussain, C.M., Raizada, P., 2025. Harnessing nitrogen doped magnetic biochar for
781 efficient antibiotic adsorption and degradation. *Journal of Industrial and Engineering*

782 Chemistry 148, 174–195. <https://doi.org/10.1016/j.jiec.2025.01.025>.

783 Ren, Z.G., Zhang, H.Y., Wang, Y.W., Lu, L., Ren, D., Wang, J.J., 2021. Multiple roles of
784 dissolved organic matter released from decomposing rice straw at different times in
785 organic pollutant photodegradation. *Journal of Hazardous Materials* 401, 123434.
786 <https://doi.org/10.1016/j.jhazmat.2020.123434>.

787 Rocci, K.S., Lavalley, J.M., Stewart, C.E., Cotrufo, M.F., 2021. Soil organic carbon response
788 to global environmental change depends on its distribution between mineral-associated
789 and particulate organic matter: A meta-analysis. *Science of The Total Environment* 793,
790 148569. <https://doi.org/10.1016/j.scitotenv.2021.148569>.

791 Shi, H.Q., Liu, G., An, X.B., Zhao, Y.J., Zheng, F.L., Li, H.R., Zhang, X.C. (John), Pan, X.C.,
792 Wu, B.L., Wang, X.S., 2024. Tracing soil erosion with Fe₃O₄ magnetic powder:
793 Principle and application. *International Soil and Water Conservation Research* 12,
794 419–431. <https://doi.org/10.1016/j.iswcr.2023.08.002>.

795 Shi, R.Y., Ni, N., Wang, R.H., Nkoh, J.N., Pan, X.Y., Dong, G., Xu, R.K., Cui, X.M., Li, J.Y.,
796 2023. Dissolved biochar fractions and solid biochar particles inhibit soil acidification
797 induced by nitrification through different mechanisms. *Science of The Total*
798 *Environment* 874, 162464. <https://doi.org/10.1016/j.scitotenv.2023.162464>.

799 Slessarev, E.W., Chadwick, O.A., Sokol, N.W., Nuccio, E.E., Pett-Ridge, J., 2022. Rock
800 weathering controls the potential for soil carbon storage at a continental scale.
801 *Biogeochemistry* 157, 1–13. <https://doi.org/10.1007/s10533-021-00859-8>.

802 Sokol, N.W., Whalen, E.D., Jilling, A., Kallenbach, C., Pett-Ridge, J., Georgiou, K., 2022.
803 Global distribution, formation and fate of mineral-associated soil organic matter under a

804 changing climate: A trait-based perspective. *Functional Ecology* 36, 1411–1429.
805 <https://doi.org/10.1111/1365-2435.14040>.

806 Stewart, C.E., Follett, R.F., Wallace, J., Pruessner, E.G., 2012. Impact of biosolids and tillage
807 on soil organic matter fractions: Implications of carbon saturation for conservation
808 management in the virginia coastal plain. *Soil Science Society of America Journal* 76,
809 1257–1267. <https://doi.org/10.2136/sssaj2011.0165>.

810 Vendig, I., Guzman, A., De La Cerda, G., Esquivel, K., Mayer, A.C., Ponisio, L., Bowles,
811 T.M., 2023. Quantifying direct yield benefits of soil carbon increases from cover
812 cropping. *Nature Sustainability* 6, 1125–1134.
813 <https://doi.org/10.1038/s41893-023-01131-7>.

814 Von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E.,
815 Marschner, B., 2007. SOM fractionation methods: Relevance to functional pools and to
816 stabilization mechanisms. *Soil Biology and Biochemistry* 39, 2183–2207.
817 <https://doi.org/10.1016/j.soilbio.2007.03.007>.

818 Wang, J.S., Li, S.C., Yin, H.M., Riaz, M., Liu, X.W., Zhang, M.Y., 2025. Biochar suppresses
819 Clubroot disease in Chinese cabbage by improving soil nutrient conditions and
820 recruiting beneficial microorganisms. *Applied Soil Ecology* 210, 106107.
821 <https://doi.org/10.1016/j.apsoil.2025.106107>.

822 Witzgall, K., Vidal, A., Schubert, D.I., Höschen, C., Schweizer, S.A., Buegger, F., Pouteau, V.,
823 Chenu, C., Mueller, C.W., 2021. Particulate organic matter as a functional soil
824 component for persistent soil organic carbon. *Nature Communications* 12, 4115.
825 <https://doi.org/10.1038/s41467-021-24192-8>.

826 Wood, S.A., Sokol, N., Bell, C.W., Bradford, M.A., Naeem, S., Wallenstein, M.D., Palm,
827 C.A., 2016. Opposing effects of different soil organic matter fractions on crop yields.
828 *Ecological Applications* 26, 2072–2085. <https://doi.org/10.1890/16-0024.1>.

829 Xie, H.T., Li, J.W., Zhu, P., Peng, C., Wang, J.K., He, H.B., Zhang, X.D., 2014. Long-term
830 manure amendments enhance neutral sugar accumulation in bulk soil and particulate
831 organic matter in a Mollisol. *Soil Biology and Biochemistry* 78, 45–53.
832 <https://doi.org/10.1016/j.soilbio.2014.07.009>.

833 Xu, C.B., Tan, X., Zhao, J.W., Cao, J.M., Ren, M., Xiao, Y., Lin, A.J., 2021. Optimization of
834 biochar production based on environmental risk and remediation performance: Take
835 kitchen waste for example. *Journal of Hazardous Materials* 416, 125785.
836 <https://doi.org/10.1016/j.jhazmat.2021.125785>.

837 Xu, S., Chen, Z., Zhang, N., Li, Y., Xu, Y., Ding, W., 2026. Soil carbon quality determined
838 the responses of respiration components to nitrogen fertilization and straw return. *Soil*
839 *Tillage Res.* 259, 107072. <https://doi.org/10.1016/j.still.2026.107072>

840 Yin, J.X., Zhao, L., Xu, X.Y., Li, D.P., Qiu, H., Cao, X.D., 2022. Evaluation of long-term
841 carbon sequestration of biochar in soil with biogeochemical field model. *Science of The*
842 *Total Environment* 822, 153576. <https://doi.org/10.1016/j.scitotenv.2022.153576>.

843 Yu, W.J., Huang, W.J., Weintraub-Leff, S.R., Hall, S.J., 2022. Where and why do particulate
844 organic matter (POM) and mineral-associated organic matter (MAOM) differ among
845 diverse soils? *Soil Biology and Biochemistry* 172, 108756.
846 <https://doi.org/10.1016/j.soilbio.2022.108756>.

847 Zhang, B.L., Jin, Y.P., Qi, J.X., Chen, H., Chen, G., Tang, S.S., 2021. Porous carbon materials

848 based on *Physalis alkekengi* L. husk and its application for removal of malachite green.
849 Environmental Technology & Innovation 21, 101343.
850 <https://doi.org/10.1016/j.eti.2020.101343>.

851 Zhang, B.L., Li, R.Q., Zheng, Y.Y., Chen, S.J., Su, Y.J., Zhou, W., Sui, Q., Liang, D.D., 2024.
852 Biochar composite with enhanced performance prepared through microbial modification
853 for water pollutant removal. International Journal of Molecular Sciences 25, 11732.
854 <https://doi.org/10.3390/ijms252111732>.

855 Zhang, G.X., Ren, R., Yan, X.R., Zhu, Y., Zhang, H.Y., Yan, G.Y., 2025. The key role of
856 magnetic iron-to-biochar mass ratios in the dissipation of oxytetracycline and its
857 resistance genes in soils with and without biodegradable microplastics. Journal of
858 Environmental Management 377, 124658.
859 <https://doi.org/10.1016/j.jenvman.2025.124658>.

860 Zhou, J.Y., Liu, Y.Y., Han, Y.T., Jing, F.Q., Chen, J.W., 2019. Bone-derived biochar and
861 magnetic biochar for effective removal of fluoride in groundwater: Effects of synthesis
862 method and coexisting chromium. Water Environment Research 91, 588–597.
863 <https://doi.org/10.1002/wer.1068>.