Wu *et al. Biochar* (2026) 8:126
https://doi.org/10.1007/s42773-026-00641-9

Biochar

RAPID REPORT Open Access

Soil-specific protection of organic carbon by biochar-derived hydroxyl radicals associated with enzyme suppression

Ping Wu[1†], Yingdong Fu[1,2†], Hailong Wang[3,4] and Shuping Qin[1*]

Abstract

The application of biochar to soils introduces persistent free radicals (PFRs), which can generate reactive oxygen species (ROS), notably hydroxyl radicals (·OH). While ·OH is known to damage extracellular enzymes involved in soil organic carbon (SOC) decomposition, its net effect on SOC mineralization and soil respiration remains complex and context-dependent. This study investigates the hypothesis that ·OH produced from biochar-derived PFRs reduces SOC mineralization by suppressing the activities of extracellular enzymes responsible for carbon decomposition. We amended three distinct soils with biochar, comparing untreated biochar (WBC) against biochar with its PFRs chemically quenched (TBC). A separate treatment quenched the soil ·OH directly. A suite of response variables, including CO_2 flux, ·OH content, and key enzyme activities, was then measured. PFR quenching reduced ·OH yield, confirming PFRs as a key ·OH source. In Black and Red soils, WBC suppressed CO_2 emissions by 6.8–12.9%, whereas TBC stimulated them. Conversely, in the Fluvo-aquic soil, both WBC and TBC increased CO_2 emissions, though TBC (with lower ·OH) caused a greater increase. Across all soils, quenching soil ·OH led to higher CO_2 emissions and DOC concentrations, alongside a significant drop in the SOC. Enzyme activities increased with PFR quenching and were the highest upon ·OH scavenging, particularly in Red soil. Our results demonstrate that biochar-derived ·OH can inhibit SOC mineralization, primarily by suppressing hydrolase activities. This protective effect is soil-specific, being overridden by positive priming in calcareous soil but dominant in acidic soils. This study underscores the soil-specific role of biochar-derived ROS in carbon cycling and highlights the need for tailored biochar management strategies.

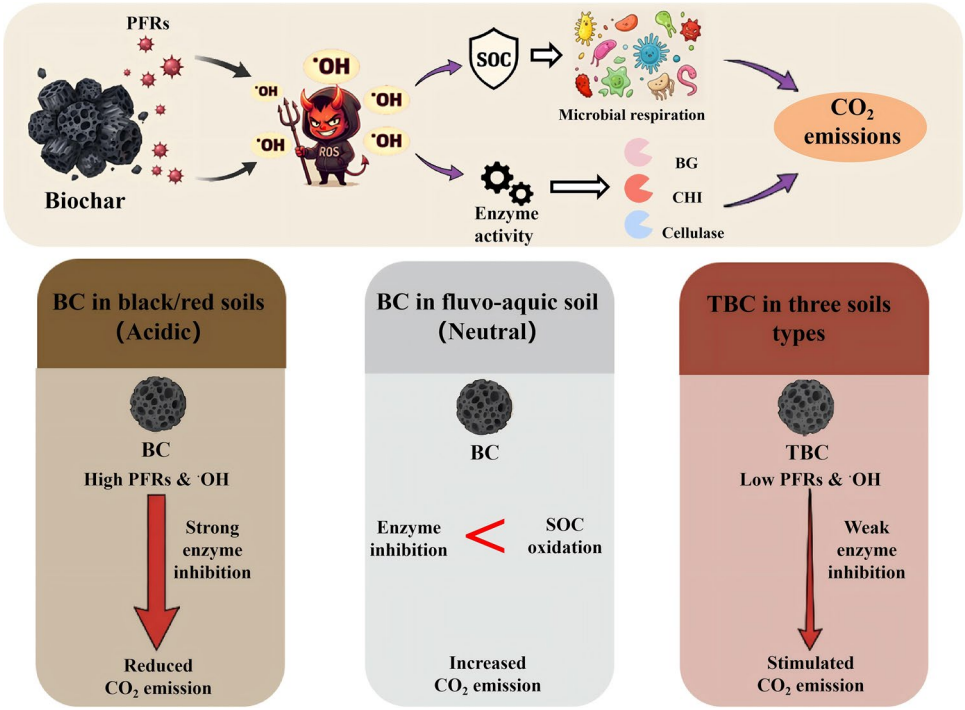
Keywords Biochar, Carbon cycling, Persistent free radicals, Reactive oxygen species, Soil type

†Ping Wu and Yingdong Fu have contributed equally to this work.

*Correspondence:
Shuping Qin
qinshuping@sjziam.ac.cn
Full list of author information is available at the end of the article

Springer

Graphical Abstract



Biochar, a carbonaceous product of biomass pyrolysis, is applied to agricultural soils to enhance fertility and promote long-term carbon sequestration (Feng et al. 2023; Luo et al. 2023). Its porous structure and chemical stability make it a potential tool for mitigating climate change through soil carbon storage (Ma et al. 2026; Weng et al. 2022). However, the biological and chemical pathways through which biochar influences SOC dynamics are multifaceted and not fully resolved. A significant yet under-characterized aspect is the presence of persistent free radicals (PFRs) within the biochar matrix. These PFRs are environmentally persistent and can catalyze molecular oxygen to yield reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), superoxide ($O_2^{\cdot-}$), and the highly reactive hydroxyl radical ($^{\cdot}OH$) (Tao et al. 2022; Wen et al. 2024).

ROS play dual roles in soil systems. They can participate in the abiotic oxidation of organic matter (Yang et al. 2025a, 2025b), yet they can also be toxic to microbial cells and destabilize extracellular enzymes (Sheng et al. 2023). Extracellular enzymes, produced by microorganisms, are the primary biological agents responsible for decomposing complex organic polymers into labile compounds (Feng et al. 2023). Their activity is thus a critical control point for SOC mineralization and CO_2 flux. Recent evidence indicates that $^{\cdot}OH$ can adsorb to mineral surfaces and cause structural damage to nearby extracellular enzymes, which rapidly reduces their catalytic capacity (Sheng et al. 2023). This presents a plausible mechanism through which biochar could attenuate, rather than stimulate, carbon loss.

Nevertheless, biochar often increases net CO_2 emissions from soil respiration, a phenomenon attributed to priming of native SOC or mineralization of labile biochar fractions (Ling et al. 2022; Zhou et al. 2025; Zimmerman et al. 2011). A fundamental paradox thus emerges: if biochar-derived $^{\cdot}OH$ inhibits carbon-degrading enzymes, why is increased CO_2 emission frequently observed? Elucidating these contradictory effects is essential for accurately predicting the carbon sequestration potential of biochar.

This study addresses the central question: Does the $^{\cdot}OH$ generated from biochar-derived PFRs suppress SOC mineralization by inactivating extracellular enzymes? We measured real-time CO_2 production, quantified $^{\cdot}OH$ generation, and assayed a suite of hydrolase activities across three soils with differing properties. The integrated approach allows us to provide new insights into the biochemical pathways governing biochar-soil-carbon interactions.

Three surface soils (0–20 cm) with different properties were collected from Luancheng Agro-Ecosystem Experimental Station (37°53′N, 114°41′E) in Hebei Province, Jiamusi Heilongjiang Province, China (47°29′N, 131°4′E), and Yingtan Red Soil Ecological Experiment Station (28°15′ N, 116°55′ E) in Jiangxi Province, China. These soil samples are classified as Fluvo-aquic soil, Black soil, and Red soil, respectively. The properties of the three soils are shown in Table S1. The biochar was derived from wheat straw via slow pyrolysis at 500 °C under oxygen-limited conditions. The PFRs in biochar were quenched using 20% and 80% triethanolamine (TEA) solutions. The quenched biochars were washed repeatedly with deionized water until the solution pH became neutral (pH ~7.1) and the solution electrical conductivity (EC) decreased to approximately 10 μS cm^{-1}. The resulting biochars were denoted as 20%TBC and 80%TBC, respectively. Raw biochar was washed using the same protocol as applied to the quenched biochar, and the resulting product was designated as WBC. The PFR concentrations in the biochars and the ·OH concentrations in biochar suspensions were determined and are shown in Text S1. For the incubation experiments, three air-dried soils were pre-incubated at 30% water-holding capacity (WHC) for 7 days. Following pre-incubation, microcosms were established using 10 g of dry soil equivalent. For biochar treatments, biochar was thoroughly mixed into the soil at 2% (w/w). All microcosms were adjusted to 60% WHC and then incubated in a temperature-controlled chamber at 25 ± 0.5 °C. Nine treatments were conducted, each with four replicates. Soil mixtures were placed in 120-mL flasks sealed with butyl rubber septa. An anaerobic headspace was created through five evacuation (0.1 kPa) and backfilling cycles with high-purity helium (120 kPa), followed by a 4-day anaerobic phase. The headspace was then replaced with a 21% O_2/79% He mixture to initiate aerobic conditions. This anaerobic-aerobic sequence simulates field redox fluctuations, which drive ·OH production. Headspace gas was sampled periodically over 7 days, and the CO_2 concentration was analyzed by gas chromatography. Cumulative CO_2 emission over the 7-day incubation was determined from the time-series CO_2 measurements. To probe the specific role of ·OH, a parallel experiment incorporated the ·OH-selective scavenger (terephthalic acid, TPA) into the soil-biochar mixtures following pre-incubation. After 7 days of incubation, ·OH generation in soil slurries was quantified using a benzoic acid probe method, where hydroxylation products were measured via high-performance liquid chromatography. The activities of three key carbon-degrading enzymes, including β-glucosidase, chitinase, and cellulase, were determined using commercial assay kits (Solarbio, China) according to the manufacturer's instructions. Dissolved organic carbon (DOC) was extracted with ultrapure water and measured on a TOC analyzer. A wet oxidation approach using potassium dichromate was adopted for SOC determination.

The TEA quenching treatment did not substantially alter the bulk physicochemical properties of biochars. As shown in Table S2, pH, EC, and elemental composition (C, H, O, N) were similar between WBC and TBC. FTIR analysis revealed only a minor increase in C–O group intensity after TEA quenching (Fig. S1), which may slightly enhance DOC release. EPR spectroscopy revealed significant concentrations of PFRs in WBC. Quenching with TEA drastically diminished PFR concentrations in WBC in a dose-dependent manner. Concurrently, TEA-quenching also suppressed ·OH generation in biochar suspensions, a trend that paralleled the PFR concentrations (Fig. 1). The observed dose–response relationship definitively establishes PFRs as the essential source for ·OH production (Fang et al. 2015). These results indicate that PFRs may function as active centers that initiate oxidative pathways in biochar-amended soils.

Biochar amendment significantly altered soil CO_2 flux and ·OH generation, but the patterns were soil-dependent (Fig. 2). In Fluvo-aquic soil, WBC addition increased cumulative CO_2 emission by 19.4% compared to the control, despite a measurable decrease in soil ·OH concentration, implying rapid consumption of ·OH through direct abiotic oxidation of SOC (Liu et al. 2024; Song et al. 2024; Yang et al. 2025a). Surprisingly, the addition of 20%TBC resulted in an even greater CO_2 emission increase, reaching 45.6% above the control. This increase occurred despite a concurrent reduction in detected ·OH by approximately 3.4% relative to the WBC treatment. When 80%TBC was applied, both ·OH suppression and CO_2 emission stimulation were more pronounced than the WBC treatment. In contrast, for both Black soil and Red soil, WBC addition significantly suppressed cumulative CO_2 emissions by 6.8% and 12.9% relative to the control, respectively. However, the introduction of TBC reversed this trend. In these soils, both 20%TBC and 80%TBC treatments stimulated CO_2 emissions above control levels (Figs. 2 and 3). This pivotal reversal indicates that in these soils, PFR-derived ·OH exerted a net suppressive effect on SOC mineralization.

The most compelling evidence was observed in the direct ·OH quenching experiment, where the addition of TPA consistently stimulated a sharp rise in CO_2 emissions across all three soil types (Fig. S2). These contrasting initial responses to WBC underscore the soil-specific dependence of biochar-induced effects. The stimulatory effect in Fluvo-aquic soil may be driven by its higher pH (Table S1), which potentially makes it more susceptible to priming from labile biochar components (Luo et al. 2023;

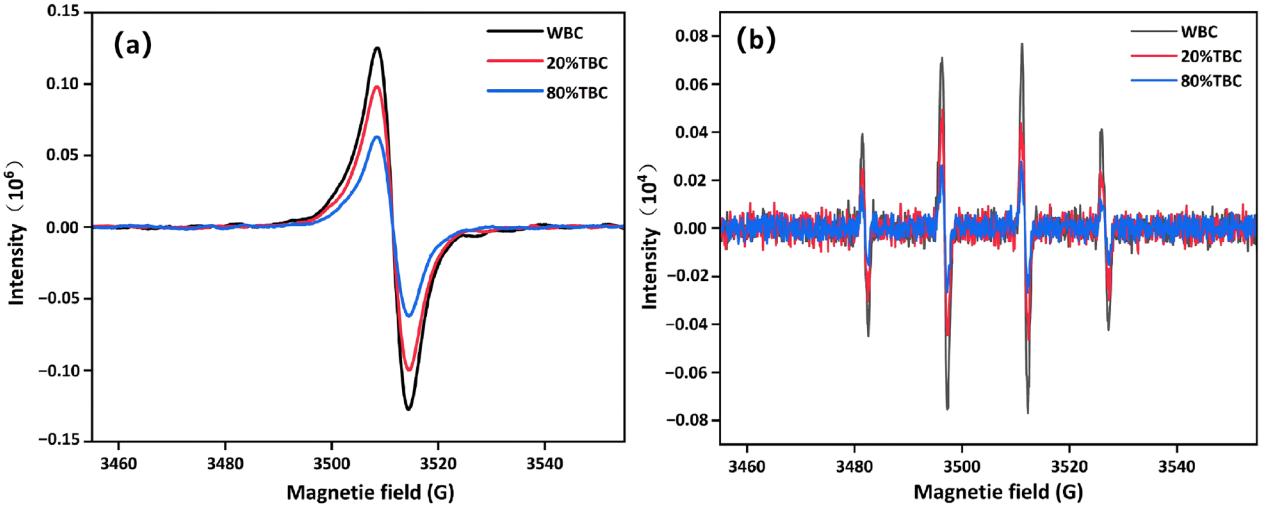


Fig. 1 EPR signals for PFRs within different biochars (**a**) and ˙OH in aqueous solution containing different biochars (**b**). WBC, 20%TBC, and 80%TBC are water-washed biochar, biochar quenched with 20% triethanolamine, and biochar quenched with 80% triethanolamine, respectively

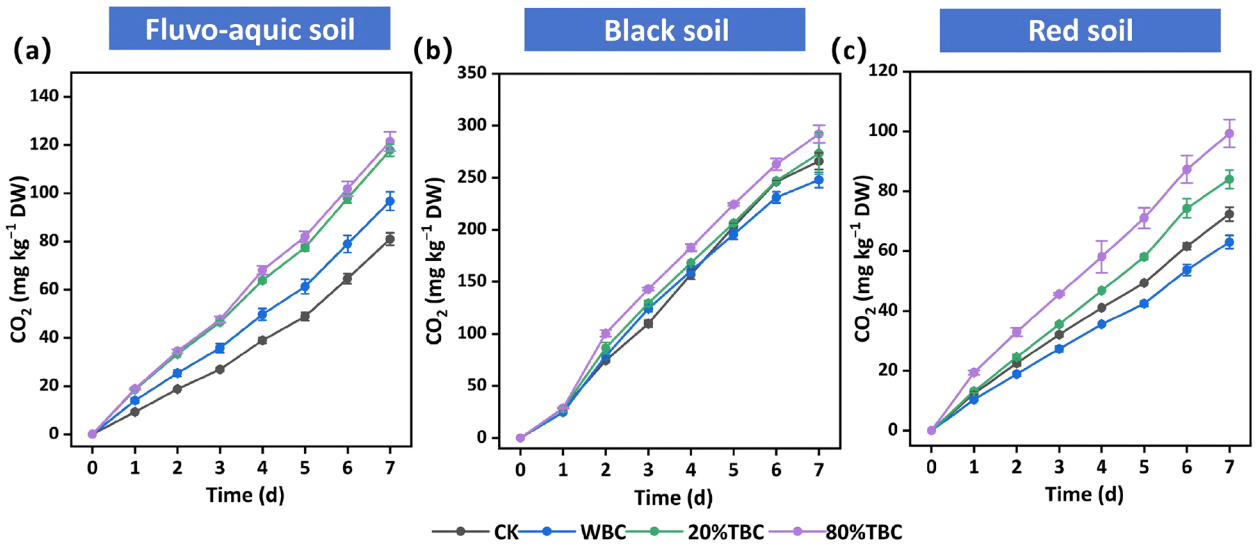


Fig. 2 Cumulative CO_2 emissions from three soils under different treatments. **a** Fluvo-aquic soil; **b** Black soil; **c** Red soil

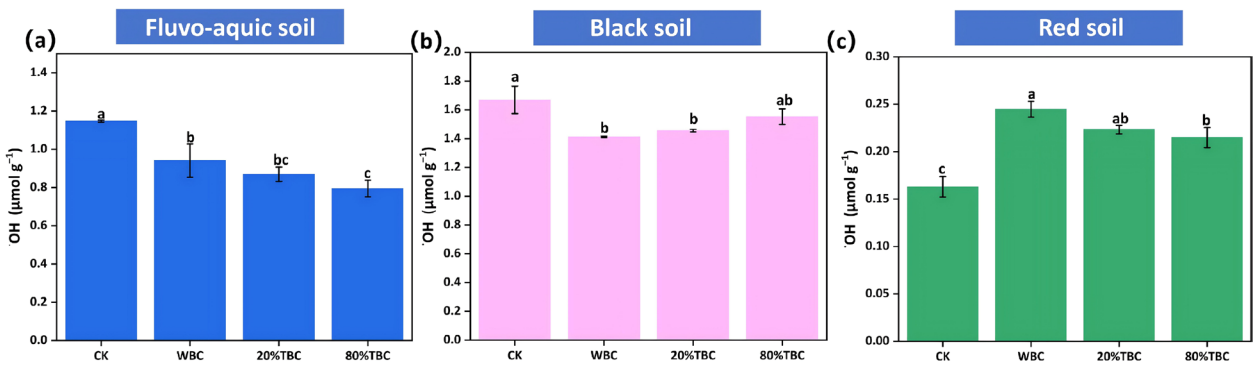


Fig. 3 ˙OH concentration in different soils under biochar treatments. Fluvo-aquic soil (**a**), Black soil (**b**), and Red soil (**c**)

Wang and Tang 2018). This effect may temporarily outweigh the ˙OH inhibition effect. The suppressive effect in Black and Red soils suggests that the ˙OH-mediated inhibition pathway is dominant in these contexts. Crucially, this reversal upon PFR quenching strongly indicates that ˙OH plays a primarily inhibitory role in these systems, and its removal unleashes a suppressed mineralization capacity.

Activities of carbon-degrading enzymes (β-glucosidase, chitinase, and cellulase) provided a mechanistic explanation for the observed CO_2 patterns (Fig. 4). Biochar addition generally increased enzyme activities relative to controls, likely due to substrate input and microbial stimulation (Ameloot et al. 2013; Lehmann et al. 2011). However, the comparison between WBC and TBC treatments was insightful. In Black and Red soils, where WBC inhibited CO_2 emissions, quenching PFRs (TBC treatments) led to a further significant increase in all enzyme activities. This implies that ˙OH generated in the WBC treatment partially suppressed enzyme function. The strongest evidence came from Red soil, which exhibited the highest enzyme activities but the lowest ˙OH levels. This inverse correlation supports the hypothesis that ˙OH acts as an enzyme inhibitor. The soil-specific response we observed arises from several interacting factors rather than a single cause. Soil pH and the contents of Fe/Al oxides appear to play dominant roles. In the acidic Black and Red soils, the high Fe/Al oxide contents promote the adsorption of extracellular enzymes onto mineral surfaces (Sheng et al. 2023). Once adsorbed, enzymes become more vulnerable to oxidative damage by ˙OH, which lowers their activity and consequently slows the decomposition of SOC. In the Fluvo-aquic soil, by contrast, the near-neutral pH and low Fe/Al oxide levels reduce enzyme adsorption. As a result, ˙OH cannot effectively suppress enzyme activity, and the positive priming effect from labile biochar components dominates, leading to increased CO_2 emission. Another contributing factor is the availability of labile carbon. The higher pH in the Fluvo-aquic soil makes biochar-derived DOC more accessible to microorganisms (Luo et al. 2023; Wang and Tang 2018), thereby promoting priming and

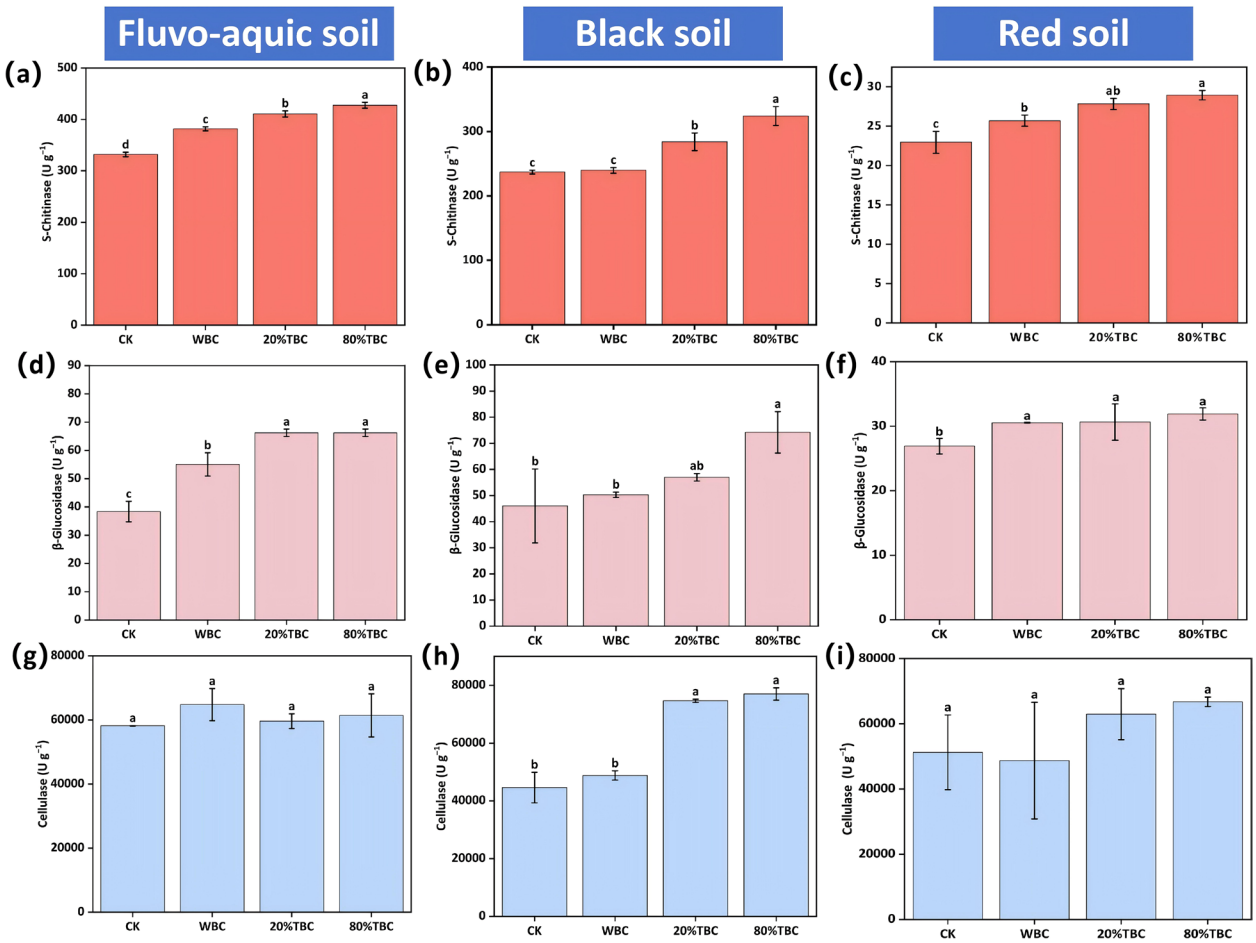


Fig. 4 Enzyme activities of the three soils amended with different biochars after incubation

outweighing the inhibitory effect of ˙OH. Although we did not directly characterize microbial communities, the observed changes in enzyme activities suggest that microbes in Fe-rich acidic soils may rely more heavily on mineral-bound enzymes, making them more sensitive to ˙OH-induced damage. In Fluvo-aquic soil, enzyme activities also further increased with TBC treatments, but the net mineralization response was likely governed by stronger positive priming from labile carbon. The TPA treatment universally yielded higher enzyme activities, confirming that even background ˙OH exerts a suppressive effect on extracellular enzymes (Fig. S3).

A striking observation was the sharp increase in DOC after TPA addition in all soils (Fig. 5). The ˙OH is a potent, non-selective oxidant capable of rapidly attacking labile organic compounds, including components of the DOC pool (Chen et al. 2020; Song et al. 2024). TPA-mediated ˙OH scavenging shields these labile DOC components from immediate oxidative mineralization to CO_2, enabling their retention in the soil solution. Concurrently, attenuating the suppressive effect of ˙OH on extracellular enzymes liberates their catalytic potential. The resultant increase in hydrolase activities accelerates the depolymerization of solid-phase organic matter and complex polymers. This enhances the production and release of low-molecular-weight DOM (Su et al. 2025; Zhao et al. 2021). The accumulated DOC subsequently serves as accessible substrate for soil microorganisms, stimulating microbial respiration and ultimately contributing to elevated CO_2 emissions. This mechanism is corroborated by the concomitant, significant decrease in SOC content observed in the TPA treatments, with the most pronounced loss occurring in Red soil (Fig. S4). This SOC depletion directly correlated with the highest cumulative CO_2 emissions recorded under the same TPA treatment in Red soil (Fig. 2). The observed inverse relationship between DOC and SOC can be attributed to the dual protective functions of ˙OH, which both suppresses enzyme-mediated SOC decomposition and promotes the oxidation of DOC. Removing ˙OH thus liberates enzymes to decompose SOC while preventing DOC oxidation, simultaneously elevating DOC and depleting SOC pools. The final net mineralization effect is determined by the dominant process in a specific soil environment.

Our integrated results have critical implications for assessing biochar's role in climate change mitigation. Biochar is often regarded as an inherently stable carbon sink, but this perspective requires refinement to account for its propensity to introduce PFRs. These radicals can trigger the loss of native SOC through ˙OH-driven processes over short to medium time scales. This phenomenon reflects an abiotic chemistry-driven "priming effect" that warrants attention. The finding that quenching radicals increases DOC and respiration further complicates the picture, suggesting that the absence of radicals may also enhance microbial activity if labile carbon is present. For carbon sequestration strategies, this implies that biochar production methods aimed at minimizing PFR formation (e.g., adjusting pyrolysis temperature or feedstock) could be beneficial to avoid unintended SOC losses. Furthermore, the interaction between biochar and soil type must be considered. In oxide-rich, acidic soils (e.g., Black and Red soil), ˙OH damages mineral-adsorbed enzymes, reducing their activity and slowing C release. In calcareous, higher-pH soil (e.g., Fluvo-aquic soil), enzymes are less adsorbed or more stable, allowing ˙OH to promote oxidation directly or via microbial stimulation. Beyond enzyme suppression, ˙OH may directly alter SOC chemistry. It could fragment organic molecules or, under some conditions, promote oxidative coupling that forms recalcitrant moieties (Li et al. 2026; Wu et al. 2026). However, our data showed that enzyme suppression plays the dominant role. Scavenging ˙OH with TPA increased SOC mineralization and enzyme activities while lowering SOC content. The rise in DOC

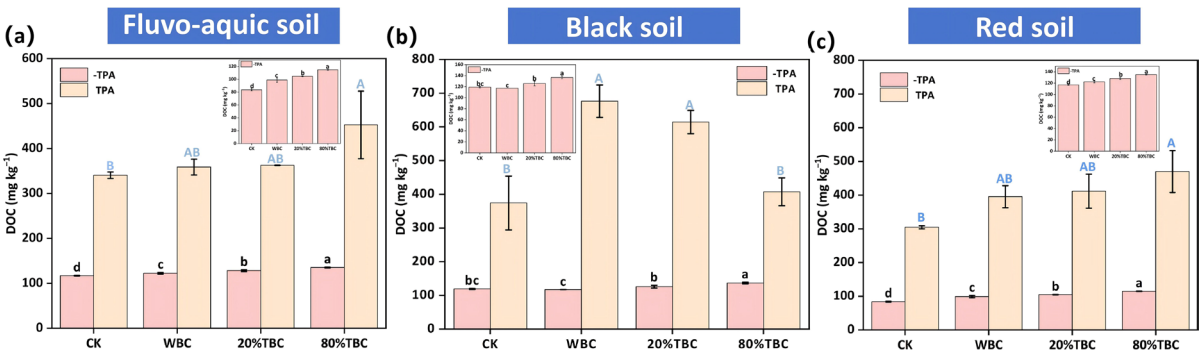


Fig. 5 Dissolved organic carbon of the three soils amended with different biochars after incubation. Fluvo-aquic soil (**a**), Black soil (**b**), and Red soil (**c**)

after ·OH removal also suggests that ·OH mainly degrades DOC rather than stabilizing it. Hence, although direct abiotic oxidation may occur, it appears to play a smaller role than enzyme-mediated suppression. The quenching experiments clearly demonstrate that PFRs in biochar are a key source of ·OH. Their net effect on C cycling requires consideration of soil mineralogy and pH. Future research should assess whether these radical-mediated processes attenuate as biochar ages and PFRs decay, and verify these laboratory-observed mechanisms at the field scale.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-026-00641-9.

Supplementary Material 1.

Acknowledgements
Not applicable.

Author contributions
Shuping Qin and Ping Wu designed the study. Yingdong Fu performed the experiments and collected and analyzed the data. Ping Wu and Yingdong Fu wrote the first draft of the manuscript. Hailong Wang contributed to revising the manuscript. All authors read and approved the final manuscript.

Funding
This work was supported by the National Key R&D Program of China (No. 2021YFD1500400), the Natural Science Foundation of Hebei Province (C2023503008), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2023000191).

Data Availability
All data generated during this study are included in this published article.

Declarations

Competing interests
Hailong Wang is an Executive Editor of the journal Biochar, and he was not involved in the peer-review or handling of the manuscript. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details
[1]Hebei Key Laboratory of Soil Ecology, Hebei Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050022, China. [2]School of Life Sciences, Institute of Life Sciences and Green Development, Hebei University, Baoding 071002, Hebei, China. [3]School of Environment and Chemical Engineering, Foshan University, Foshan 528000, Guangdong, China. [4]Guangdong Provincial Key Laboratory of Integrated Agro-Environmental Pollution Control and Management, Institute of Eco-Environmental and Soil Sciences, Guangdong Academy of Sciences, Guangzhou 510650, China.

Received: 10 February 2026 Revised: 15 May 2026 Accepted: 1 June 2026
Published online: 06 July 2026

References

Ameloot N, Graber ER, Verheijen FGA, De Neve S (2013) Interactions between biochar stability and soil organisms: review and research needs. Eur J Soil Sci 64:379–390. https://doi.org/10.1111/ejss.12064

Chen C, Hall SJ, Coward E, Thompson A (2020) Iron-mediated organic matter decomposition in humid soils can counteract protection. Nat Commun. https://doi.org/10.1038/s41467-020-16071-5

Fang GD, Liu C, Gao J, Dionysiou DD, Zhou DM (2015) Manipulation of persistent free radicals in biochar to activate persulfate for contaminant degradation. Environ Sci Technol 49:5645–5653. https://doi.org/10.1021/es5061512

Feng J, Yu D, Sinsabaugh RL, Moorhead DL, Andersen MN, Smith P, Song Y, Li X, Huang Q, Liu Y-R, Chen J (2023) Trade-offs in carbon-degrading enzyme activities limit long-term soil carbon sequestration with biochar addition. Biol Rev 98:1184–1199. https://doi.org/10.1111/brv.12949

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota - a review. Soil Biol Biochem 43:1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Li Z, Li X, Yang Y, Li J, Wang H, Tang L, Gu L, Ai H, Jiao B, Pan W (2026) Soil organic matter modulation during redox oscillations: insights from iron speciation and microbial metabolism. Environ Sci Technol 60:7111–7122. https://doi.org/10.1021/acs.est.5c14988

Ling L, Luo Y, Jiang B, Lv J, Meng C, Liao Y, Reid BJ, Ding F, Lu Z, Kuzyakov Y, Xu J (2022) Biochar induces mineralization of soil recalcitrant components by activation of biochar responsive bacteria groups. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2022.108778

Liu FH, Ding YY, Liu J, Latif J, Qin JJ, Tian SX, Sun SY, Guan BT, Zhu KC, Jia HZ (2024) The effect of redox fluctuation on carbon mineralization in riparian soil: an analysis of the hotspot zone of reactive oxygen species production. Water Res. https://doi.org/10.1016/j.watres.2024.122294

Luo L, Wang J, Lv J, Liu Z, Sun T, Yang Y, Zhu Y-G (2023) Carbon sequestration strategies in soil using biochar: advances, challenges, and opportunities. Environ Sci Technol 57:11357–11372. https://doi.org/10.1021/acs.est.3c02620

Ma S, Cao Y, Lu J, Lu Z, Zhu J, Zhang W, Li X (2026) Organic amendment increases soil carbon sequestration by altering carbon stabilization pathways within soil aggregates. Soil Till Res. https://doi.org/10.1016/j.still.2025.106868

Sheng Y, Hu J, Kukkadapu R, Guo D, Zeng Q, Dong H (2023) Inhibition of extracellular enzyme activity by reactive oxygen species upon oxygenation of reduced iron-bearing minerals. Environ Sci Technol 57:3425–3433. https://doi.org/10.1021/acs.est.2c09634

Song W, Clough T, Hou H, Qin S (2024) Nitrate-induced hydroxyl radical releases deep soil organic carbon by opening the "enzyme latch" under micro-aerobic conditions. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2024.109389

Su LF, Liu Y, Tan LS, Zhou XL, Wang T, She YY, Huang JF, Cai YB, Li SH, Guo PP, Luo M (2025) Hydrolase-oxidase responses mediate distinct carbon dynamics following wetland conversion to paddy versus upland systems. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2025.109973

Tao W, Zhang P, Li H, Yang Q, Oleszczuk P, Pan B (2022) Generation mechanism of persistent free radicals in lignocellulose-derived biochar: roles of reducible carbonyls. Environ Sci Technol 56:10638–10645. https://doi.org/10.1021/acs.est.1c06997

Wang X, Tang C (2018) The role of rhizosphere pH in regulating the rhizosphere priming effect and implications for the availability of soil-derived nitrogen to plants. Ann Bot 121:143–151. https://doi.org/10.1093/aob/mcx138

Wen Z, Shi X, Gu Y, Ma K, Song X, He A, Wang C, Zhang N, Sui H, Xu C, Xue R (2024) Enhanced Fenton performance of wet-mechanochemically synthesized FeS 2 /Biochar: the multiple synergistic effect derived from mutual element doping. Chem Eng J. https://doi.org/10.1016/j.cej.2024.152080

Weng ZH, Van Zwieten L, Tavakkoli E, Rose MT, Singh BP, Joseph S, Macdonald LM, Kimber S, Morris S, Rose TJ, Archanjo BS, Tang C, Franks AE, Diao H et al (2022) Microspectroscopic visualization of how biochar lifts the soil organic carbon ceiling. Nat Commun 13:5177. https://doi.org/10.1038/s41467-022-32819-7

Wu T, Qin J, Wang S, Sun H, Hu X, Li K (2026) Reactive oxygen species in soil: a comprehensive review. Soil Syst 10:10050052. https://doi.org/10.3390/soilsystems10050052

Yang K, Jia B, Liu J, Zhu K, Qin J, Jia H (2025a) A novel perspective on the role of hydroxyl radicals in soil organic carbon mineralization within the detritusphere: stimulating C-degrading enzyme activities. Environ Sci Technol 59:5045–5055. https://doi.org/10.1021/acs.est.4c13619

Yang K, Liu J, Wang Z, Zhu K, Jia B, Yang H, Qin J, Xie J, Latif J, Liu F, Li Y, Chen N, Jia H (2025) Spatiotemporal dynamics of reactive oxygen species in the detritusphere and their critical roles in organic carbon mineralisation. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2024.109700

Zhao Y, Xiang W, Huang C, Liu Y, Tan Y (2021) Production of hydroxyl radicals following water-level drawdown in peatlands: a new induction mechanism for enhancing laccase activity in carbon cycling. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2021.108241

Zhou X, Feng Z, Yao Y, Liu R, Shao J, Jia S, Gao Y, Xue K, Chen H, Fu Y, He Y (2025) Nitrogen input alleviates the priming effects of biochar addition on soil organic carbon decomposition. Soil Biol Biochem. https://doi.org/10.1016/j.soilbio.2024.109689

Zimmerman AR, Gao B, Ahn M-Y (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol Biochem 43:1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005