



Supplement of

Biochar addition enhances soil aggregate stability by modulating soil internal forces: the critical role of readily oxidized organic carbon and particulate organic carbon

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1. Calculation of soil surface electrochemical properties

The calculation formula for parameters related to the electrochemical properties of the soil surface is as follows:

a. Surface potential ϕ_0 :

$$\phi_0 = \frac{2RT}{2(\beta_{Ca} - \beta_{Na})F} \ln \frac{a_{Ca}^0 N_{Na}}{a_{Na}^0 N_{Ca}} \quad (1)$$

where ϕ_0 (V) is the surface potential; R ($J K^{-1} mol^{-1}$) is the ideal gas constant; T (K) is the absolute temperature; F ($C mol^{-1}$) is the Faraday constant; β_{Ca} and β_{Na} are the effective charge coefficients of Ca^{2+} and Na^+ , respectively, with $\beta_{Ca} = -0.0213 \ln(I^{0.5}) + 1.2331$ and $\beta_{Na} = 0.0213 \ln(I^{0.5}) + 0.766$; I ($mol L^{-1}$) is the ionic strength; a_{Na}^0 ($mol L^{-1}$) and a_{Ca}^0 ($mol L^{-1}$) are the activities of Na^+ and Ca^{2+} in solution; and N_{Na} ($mol g^{-1}$) and N_{Ca} ($mol g^{-1}$) are the amounts of Na^+ and Ca^{2+} adsorbed by the soil.

b. Surface charge density σ_0 :

$$\sigma_0 = \text{sgn}(\phi_0) \sqrt{\frac{\epsilon RT}{2\pi} \left(a_{Na}^0 e^{\frac{\beta_{Na} F \phi_0}{RT}} + a_{Ca}^0 e^{\frac{2\beta_{Ca} F \phi_0}{RT}} \right)} \quad (2)$$

In the equation: σ_0 ($C m^{-2}$) is the surface charge density of soil particles; ϵ is the dielectric constant of water, with a value of $8.9 \times 10^{-10} C^2 J^{-1} dm^{-1}$.

c. Surface electric field strength E_0 :

$$E_0 = \frac{4\pi}{\epsilon} \sigma_0 \quad (3)$$

In the equation: E_0 ($V m^{-1}$) is the surface electric field strength.

d. Specific surface area S :

$$S = \frac{N_{Na} \kappa}{m a_{Na}^0} e^{\frac{\beta_{Na} F \phi_0}{2RT}} = \frac{N_{Ca} \kappa}{m a_{Ca}^0} e^{\frac{\beta_{Ca} F \phi_0}{RT}} \quad (4)$$

In the equation: $S \text{ (m}^2 \text{ g}^{-1}\text{)}$ is the specific surface area; $m = 0.5259 \ln(c_{\text{Na}}^0/c_{\text{Ca}}^0) + 1.992$; $\kappa \text{ (dm}^{-1}\text{)}$ is the Debye parameter, and its reciprocal κ^{-1} represents the thickness of the diffusion double layer of colloidal particles, calculated as follows:

$$\kappa = \sqrt{\frac{8\pi F^2 C_0}{\varepsilon RT}} \quad (5)$$

e. Surface charge number (SCN):

$$SCN = 10^5 \frac{S\sigma_0}{F} \quad (6)$$

In the equation: $SCN \text{ (cmol(c) kg}^{-1}\text{)}$ is the surface charge number.

2. Calculation of soil internal forces

The SIF interactions between soil particles at the mesoscopic scale mainly include electrostatic repulsive pressure (P_E), surface hydration repulsive pressure (P_h), and van der Waals attractive pressure (P_{vdw}). The net inter-particle force (P_{net}) is the combined force of the three, which can be calculated from the soil surface property parameter to obtain the SIFs, calculated as follows.

Electrostatic repulsive pressure (P_E):

$$P_E = \frac{2}{101} RT c_0 \left\{ \cosh \left[\frac{ZF\phi(d/2)}{RT} \right] - 1 \right\} \quad (7)$$

Where $P_E \text{ (atm)}$ is the electrostatic repulsive pressure; $c_0 \text{ (mol L}^{-1}\text{)}$ denotes the concentration of ions in the native solution; $d \text{ (dm)}$ is the distance between neighboring particles; $\phi(d/2) \text{ (V)}$ is the midpoint potential at the overlap of the particle bilayers; and Z denotes the valence of the cation.

Surface hydration repulsive pressure (P_h):

$$P_h = 3.33 \times 10^4 e^{-5.76 \times 10^9 d} \quad (8)$$

Where P_h (atm) is the surface hydration repulsive pressure; d (dm) denotes the distance from the particle surface.

Van der Waals attractive pressure (P_{vdw}):

$$P_{vdw} = -\frac{A_{eff}}{0.6\pi} (10d)^{-3} \quad (9)$$

Where P_{vdw} (atm) is van der Waals attractive pressure; A_{eff} (J) is Hamaker constant.

Hamaker constant was determined using the method proposed by Tuller and Or. (2005). Weigh 10 g of soil samples sieved through a 2 mm mesh and place them in an aluminum box. Add varying volumes of water to the samples, mix thoroughly, seal with plastic film, and allow them to equilibrate for one week. Soil water potential at different moisture contents was measured using a dew point water potential meter (WP4-T). The samples were then weighed, dried at 105 °C, and re-weighed to calculate the soil water content. Hamaker constant was obtained by fitting the soil water potential to the water content through the following model.

$$\theta_m = -\rho_w S \left(\sqrt[3]{\frac{A_{eff}}{6\pi\rho_w g \psi}} \right) \quad (10)$$

Where θ_m (kg kg⁻¹) is the soil water content; ρ_w (kg m⁻³) is the density of water; S (m² g⁻¹) is the SSA of the soil; A_{eff} (J) is the Hamaker constant; and g (m s⁻²) is the acceleration of gravity; ψ (m H₂O) is the soil water potential.

Net force (P_{net}):

$$P_{net} = P_E + P_h + P_{vdw} \quad (11)$$

Table S1 Soil electrochemical properties under biochar treatment for 365 days

Treatment	SCN (cmol(c) kg ⁻¹)	SSA (m ² g ⁻¹)	σ_0 (c m ⁻²)
CK	18.90 ± 0.88d	41.75 ± 2.34e	0.44 ± 0.04a
M1	21.23 ± 0.49c	51.05 ± 3.83d	0.40 ± 0.02ab
M3	22.26 ± 1.41c	54.72 ± 6.84d	0.39 ± 0.03b
M5	24.74 ± 0.70b	61.71 ± 4.45c	0.39 ± 0.02b
M10	28.09 ± 1.16a	70.81 ± 3.98ab	0.38 ± 0.01b
W1	21.81 ± 0.83c	52.29 ± 0.65d	0.40 ± 0.02ab
W3	22.43 ± 0.39c	55.30 ± 2.30d	0.39 ± 0.01b
W5	26.12 ± 0.65b	64.88 ± 3.73bc	0.39 ± 0.03b
W10	29.34 ± 0.76a	72.96 ± 1.79a	0.39 ± 0.01b

Note: M1, M3, M5, M10, add 1%, 3%, 5%, 10% maize straw biochar; W1, W3, W5, W10, add 1%, 3%, 5%, 10% wheat straw biochar; CEC: cation exchange capacity, SSA: specific surface area, σ_0 : surface charge density; Values are means ± stand deviation (n = 3).

Figure S1 Effect of biochar addition on soil active organic carbon fractions after 365 days. M1, M3, M5, M10, add 1%, 3%, 5%, 10% maize straw biochar; W1, W3, W5, W10, add 1%, 3%, 5%, 10% wheat straw biochar.

Figure S2 Soil aggregate breaking strength ($< 5 \mu\text{m}$, $< 10 \mu\text{m}$) at different electrolyte concentrations under biochar addition after 365 days of incubation. M1, M3, M5, M10, add 1%, 3%, 5%, 10% maize straw biochar; W1, W3, W5, W10, add 1%, 3%, 5%, 10% wheat straw biochar.

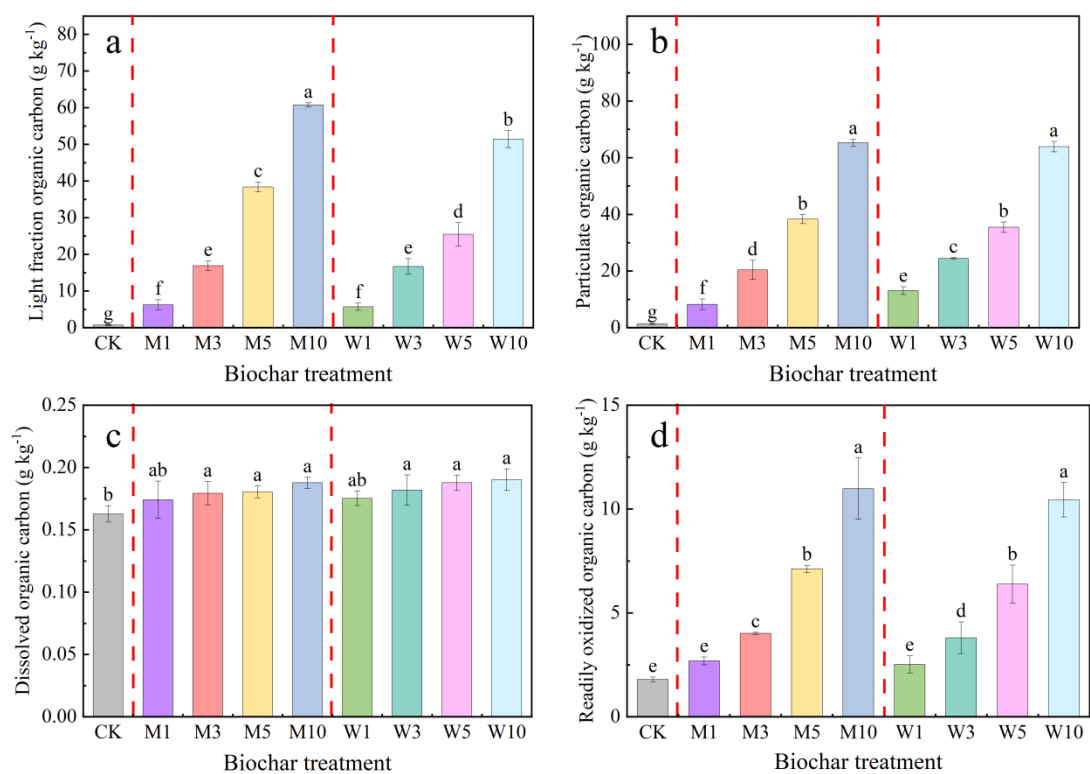


Fig. S1. Effect of biochar addition on soil active organic carbon fractions after 365 days.

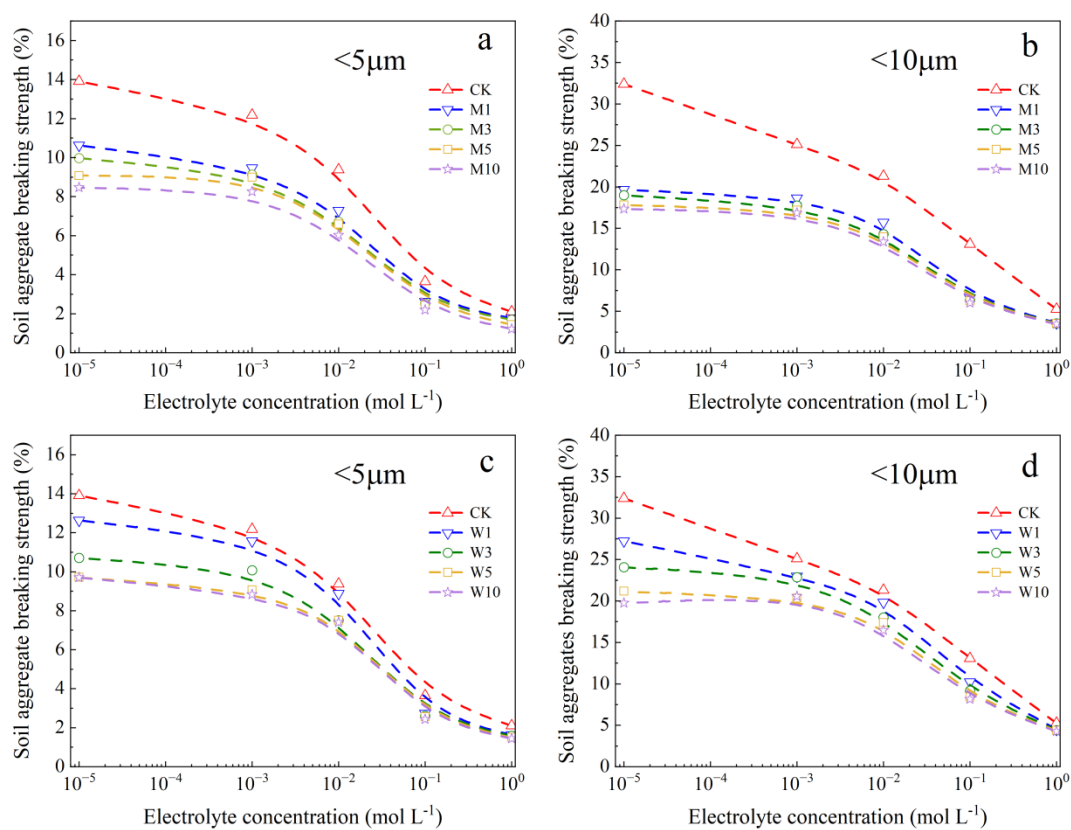


Fig. S2. Soil aggregate breaking strength (< 5 μm, < 10 μm) at different electrolyte concentrations under biochar addition after 365 days of incubation.