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Biochar

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Weathering of biochar: implications to soil health, carbon sequestration and soil remediation

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Abstract

There has been increasing interest in the application of biochar as a soil amendment to sequester carbon and remediate contamination. The novelty of this review is that it provides thorough bibliometric analysis and critical discussions on various processes of biochar weathering, factors affecting the weathering processes, and the implication of biochar weathering on its potential value for carbon sequestration and soil remediation in relation to promoting soil health. Although biochar contains stabilized carbon, when exposed in the field, biochar undergoes physical, chemical, and biological weathering processes, which could lead to fragmentation of biochar, impacting its nature, characteristics, and reactivity. The weathering of biochar in soil is impacted by the nature of biochar, soil type, cultivation practices, and environmental conditions. This review will advance the existing knowledge on how weathering-initiated changes in biochar alter the interactions between biochar and soil components significantly, including microorganisms. Therefore, this article will provide core perspectives on how these events impact carbon sequestration, contaminant remobilization, soil health, and soil remediation potentials of biochar.

Highlights

- Biochar undergoes physical, chemical and biological weathering processes in soil.
- Physical weathering leads to the formation of micro- and nano-biochar fragments.
- Chemical/biological weathering leads to changes in biochar aromatic structure.
- Biochar weathering leads to a decrease in carbon sequestration in soil.
- Biochar weathering impacts soil health through adsorption/desorption of contaminants.

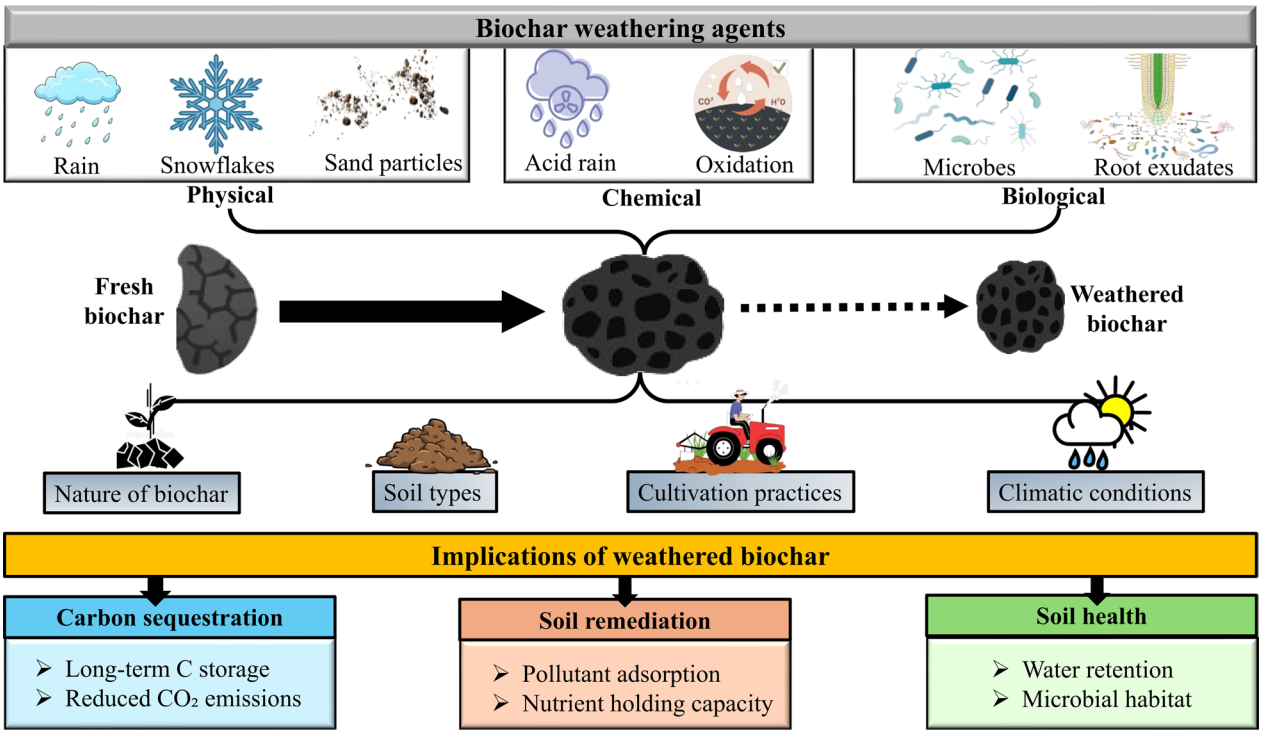
Keywords Contamination, Weathering, Remediation, Soil health, Carbon sequestration

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Graphical Abstract



1 Introduction

Biochar is produced through anaerobic pyrolysis of biomass, and biochar has multifunctional applications including nutrient and microbial carrier, catalyst, soil amendment and animal feed. Recently, there has been increasing interest in the application of biochar as a soil amendment to sequester carbon (C) (Gross et al. 2021) and remediate contamination (Bolan et al. 2021; Amalina et al. 2022). Biochar contains a large proportion of stable C (>90%), which provides C sequestration potential in addition to co-benefits in improving soil health. Similarly, biochar is effective in the immobilization of both inorganic (e.g., potentially toxic elements such as cadmium and arsenic) and organic (e.g., persistent organic pollutants (POPs) such as pesticides and per- and poly fluoroalkyl substances), thereby mitigating their bioavailability and ecotoxicity (Afshar and Mofatteh 2024; Kabir et al. 2023). Although biochar contains stable carbon, when exposed in the field, biochar is subjected to physical, chemical and biological weathering (i.e., aging) processes, which could lead to fragmentation affecting its nature, characteristics and reactivity (Spokas et al. 2014; Mia et al. 2017; Zhong et al. 2020). These weathering-initiated changes in biochar are likely to alter significantly the interactions between biochar and soil components including microorganisms, thereby impacting C sequestration and soil remediation potentials of biochar (Mia et al. 2017).

Biochar exposed to the natural environment including soil is subjected to a range of weathering processes that are influenced by solar-radiation, moisture, temperature, oxygen, pH, salinity (electrical conductivity), nutrients, and contaminants as well as microbial activity. The weathering of biochar initiates even during its cooling and storage, which is partly governed by the contact with atmospheric moisture and other environment factors (Mia et al. 2017). Biochar weathering is accelerated after application to soil through physical and biochemical processes. Physical weathering of biochar occurs mainly through mechanical actions (Mia et al. 2017), while chemical weathering occurs due to the influence of moisture and oxygen in the soil (Spokas 2013). Solar-derived ultraviolet (UV) radiation with high energy and soil microorganisms also play a critical role in the weathering of biochar (Wang et al. 2020a).

While it has been demonstrated that biochar undergoes various weathering processes in soil which impact its potential value for C sequestration and soil remediation

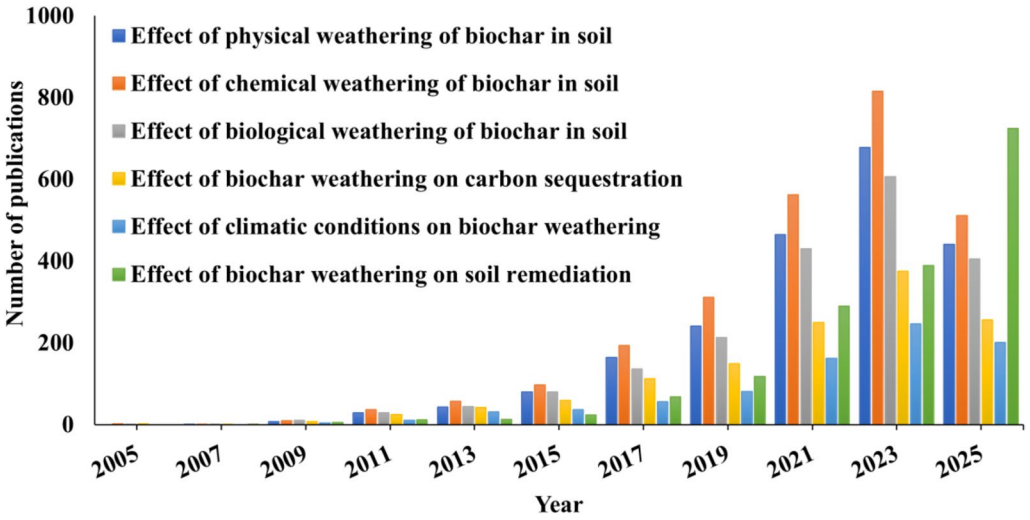


Fig. 1 The number of publications on weathering of biochar over the last 20 years

(Naisse et al. 2015; Zhong et al. 2020), there have been only limited number of reviews on this emerging topic (Mia et al. 2017). These reviews have focused mostly on the various weathering/aging processes of biochar with limited information on the implication of weathering on its potential value for C sequestration and soil remediation. The overall aim of this review is to provide a bibliometric analysis of critical discussions on various processes of biochar weathering, factors affecting the weathering processes, and the implication of biochar weathering on its potential value for C sequestration and soil remediation. The specific objectives of the review include: (i) to describe the various physical, chemical and microbial processes involved in the weathering of biochar; (ii) to understand the molecular and surface transformations of biochar as impacted by these weathering processes and the factors affecting weathering; (iii) to examine the effect of weathering of biochar on its long-term C sequestration potential, and its value as a soil amendment in improving soil properties and remediation of contaminants.

2 Review methodology

A literature search was conducted in Web of Science Core Collection on May 30, 2025, with the following search terms: TS (topic search) = ("Biochar" OR "Weathering) AND TS = ("physical weathering" OR "Chemical weathering "OR "microbial weathering" OR "Microbial mineralization") AND TS = ("carbon sequestration" OR "oxidation" OR "disintegration" OR "priming effect" OR "soil remediation"). A total of 10,689 results were retrieved from the initial search from online literature databases. These consisted of conference proceedings, book chapters, editorial materials, non-English articles, and publications not matching with the targeted keywords. Once the dataset was limited to relevant peer reviewed research articles and reviews in English, the total number of eligible records was reduced to 4236. The keyword analysis algorithm was used to extract 439 keyword collections from 4236 articles on "weathering/aging of biochar" and "carbon sequestration" published between 2005 and 2025 (Fig. 1). A PRISMA flow chart was used to highlight the review's content and improve its quality by establishing a rigorous methodological framework and providing a more thorough synthesis of relevant studies (SI Fig. 1). The results were visualized using the VOSviewer software (version 1.6.20). This keyword co-occurrencemap shows the 196 most common keywords (minimum occurrence ≥ 4) and their relationships to each other. A minimum co-occurrence threshold of 4 was chosen since it produced an optimal balance between retaining meaningful terms as high frequency and discarding low frequency non-informative keywords. Different colours in the map indicate different clusters of themes: (i) biochar physico-chemical properties and pyrolysis processes (red); (ii) soil interaction, carbon sequestration, and agricultural use (green); and (iii) soil pollutants and heavy-metal immobilization (blue). The cluster pattern maps (i.e. clustering results) show the main research hotspots and conceptual relationships that govern global research on biochar weathering.

The terms 'weathering' and 'aging' of biochar are used interchangeably to represent the changes in its properties when fresh biochar is subjected to various physical, chemical and biological weathering/aging processes in soil (Zeba et al. 2022). Standardized methods for

evaluating biochar weathering primarily involve laboratory simulations of environmental conditions and long-term field studies, guided by methodologies proposed by International Biochar Initiative (IBI) and the European Biochar Certificate (EBC) (IBI 2015; EBC 2025). The laboratory-based accelerated weathering methods involve the incubation of biochar samples in a solution containing dissolved organic carbon or microbial inoculants to assess changes in properties and degradation under simulated natural weathering conditions such as wetting/drying and freezing/thawing cycles to speed up the weathering process. The field-based natural weathering involves applying biochar to field plots and monitoring changes over long periods under natural environmental conditions. This provides the most realistic data on long-term stability and behavior in a specific soil type and climate.

3 Biochar weathering processes

Although biochar is commonly referred to as "stable carbon", when exposed to the environment, biochar is subjected to mechanical stresses, chemical species, and biological processes, which do alter the physical and chemical properties of the original/pristine biochar (Table 1). These processes are referred to generally as "biochar weathering". Analogous to Jenny (1941) soil formation factors, biochar weathering in soil can be expressed:

$$BCWeathering = f(Biochar, Soil, Climate, BurialDepth, Tillage, Time),$$

where:

Biochar = f (feedstock, particle size, pyrolysis temperature, heating/cooling rates, post-production activation); Soil = f (Climate, parent material, organisms, topography, time);

Climate would be a function of the solar radiation (UV) exposure, temperatures, precipitation, and wind speed; Burial depth is the depth at which biochar is buried, Tillage is by type and frequency, and Time is duration of soil exposure. Analogous to Jenny's model, these are solely descriptive equations but provide an overview of the complexity and far-reaching extent of the interconnected processes involved in the biochar weathering (Fig. 2).

3.1 Physical weathering

Physical weathering of biochar occurs mainly through mechanical actions including soil cultivation (Li et al. 2018), wetting/drying (Xu et al. 2018; Wang et al. 2020a), freezing/thawing (Shen et al. 2024), soil grain abrasion (Ravi et al. 2016), and biological perturbation (Ameloot et al. 2013; Ferreira et al. 2021). Physical swelling of biochar from water absorption can lead to an increase in the spacing between the graphic sheets(Spokas et al. 2014). The exfoliation of these sheets results in the physical disintegration of biochar (Cao et al. 2019; Wang et al. 2020a). Additionally, it has been observed that these exfoliated particles often possess significantly higher surface areas (Roy et al. 2019) and therefore potential increases in surface chemical reactions as well as chemical sorption capacities (Liang et al. 2024). However, Du et al. (2023) observed that while the post-interaction of large particle size fractions of biochar (250–425 μm) with kaolinite and montmorillonite during the weathering process showed increases in both the surface area and Cd sorption capacity, the small particle size fractions (25–75 μm) showed an opposite trend, which they attributed to the blocking of biochar pores by clay minerals. Mechanical attrition of biochar particles has also been observed to alter their potential mobility in the soil environment (Wang et al. 2019) as well as the response of soil and plant responses following biochar amendment (Liao and Thomas 2019). Furthermore, changes in the physical structure (along with other chemical weathering) has been observed to alter the availability of sorbed heavy metals in manure biochar, leading to their release, potentially poising unaccounted environmental risks after soil weathering (Wang et al. 2021a).

Physical breakdown of biochar particles can also increase wind erosional losses. Biochar application increased the particulate emissions from biochar-amended soils in a wind tunnel through direct transport of small biochar particles from the soil surface (< 100 μm), as well as the accelerated formation of fine biochar particles through mechanical breakdown of larger biochar particles by abrasion of sand size soil particles (Ravi et al. 2016). Additionally, Li et al. (2018) observed that the formation of fine biochar particles was feedstock- and pyrolysis temperature-dependent, with the dominant biochar particle size being larger than 10 μm. It is interesting to note that comminution has been observed to generate higher free radical concentration on coal (Dalal et al. 1989) and especially grinding actions (Liu et al. 2014). Although no specific studies directly investigating biochar were located, it is a sound hypothesis that grinding and mechanical breakdown of biochar particles could result in similar observations. Thereby, increasing the frequency of free-radical contributions to electrochemical reactions as well as catalyzing biochar reactions resulting from particle size reduction in the environment.

There have been only limited studies examining the impact of mechanical attrition of biochar particles.

Table 1 Summary of selected studies depicting quantitative information on biochar weathering rates

Biochar type	Pyrolysis temperature	Soil type	Timescale and condition (*)	Total carbon (TC) change (%)	Weathering rate (% yr^{-1})	Transport distance	pH change (fresh → aged)	Observation	Reference
Vineyard pruning residue biochar	700 °C	Eutric Cambisol	2 years, field experiment	Net TC loss: 13 ± 5%	~6.5	NA	9.96 → 7.50	This drop is partly because dissolved organic carbon (DOC) leaches out, and labile biochar C breaks down through redox reactions and interactions with soil	Rombolà et al. (2023)
Chipped hardwood biochar (peach, grapevine pruning wood)	550 °C	Sandy loam Inceptisol	4 years, field experiment	Net TC loss: 14.5 ± 0.18%	~3.6	–	9.97 → 8.08	Carboxylic groups form when weathering breaks down basic sites, which lowers the pH of biochar by about 2 units. The loss of TC was partly due to the mineralisation of labile carbon	Sorrenti et al. (2016)
Hardwood biochars (BC1: slow pyrolysis; BC2: wood pellet; BC3: macadamia shell)	500–550 °C	Silt loam	3 years, field experiment	Net TC loss: ~ 16%	~5.3	0–15 cm	BC1: 7.4 → 6.4; BC2: 10.1 → 5.7; BC3: 7.5 → 5.4	The difference in C content may reflect variations in biochar particle properties, not only carbon loss due to weathering	Spokas (2013)
Oak, pine, and grass biochars	250, 400, 650 °C	Fine sandy Entisol and forest Spodosol	15 months (~ 1.25 years), field experiment	Net TC change: + 5%**	–	–	6.3 → 5.3	The carbon content was raised solely in the high-temperature and grass biochars, while the accumulation of ash during aging was notable only in the case of low-temperature biochar	Mukherjee et al. (2014)
Rice husk + cotton seed hull biochar	400 °C	Fluvisol	5 years, field experiment	Net TC change: + 0.7%**	–	20–40 cm	–	Biochar ageing smoothened the surface and enlarged the pore size with a loss of small pores from depleted labile organic carbon or carbonates	Dong et al. (2017)

Table 1 (continued)

Biochar type	Pyrolysis temperature	Soil type	Timescale and condition (*)	Total carbon (TC) change (%)	Weathering rate (% yr^{-1})	Transport distance	pH change (fresh → aged)	Observation	Reference
Biochars from pine wood, paper sludge, sewage sludge, vineyard wood, wood chips	450–620 °C	Calcic Cambisol	24 months (2 years), field experiment	Net TC loss: 16%	~8.0	–	9.2–9.4 → 7.7–7.9	Biochars become less aromatic and more functionalized as they age, with aryl C decreasing (≤ 11%) and alkyl and O-alkyl C increasing	de la Rosa et al. (2018)
Corn straw biochar	550 °C	Mollisols	> 1-month, artificial aging (CDWs, CFTs)	Net TC loss: CDWs ~ 8.69%; CFTs ~ 7.65%	–	–	CDWs: 9.91 → 4.92; CFTs: 9.91 → 4.99	The process of strong oxidation taking place during CDWs and CFTs led to the deterioration of the biochar carbon structure and the generation of functional groups containing oxygen	Cui et al. (2024)
Maize straw biochars	300, 450, 600 °C	Sandy loam	360 days (almost 1 year), incubation experiment	Net TC change: + 1.41%**	–	–	7.9 → 7.9	Higher CO_2 emissions from soil are associated with changes in microbial communities caused by aged biochars	Yang et al. (2022a, b, c)
Pine wood chip biochars	350, 550 °C	NA	6 years, incubation with physical, chemical and biological aging	350 °C: Net TC loss: 14% (physical);Net TC change: + 5%** (chemical); 5% (biological) 550 °C: Net TC loss: 6% (physical); 4% (chemical); 8% (biological)	350 °C: ~ 2.3 (physical); ~ 0.8 (biological) 550 °C: ~ 1.0 (physical); ~ 0.7 (chemical); ~ 1.3 (biological)	–	350 °C: Physical 6.1 → 3.0; Chemical 6.1 → 4.3; Biological 6.1 → 4.8 550 °C: Physical 6.9 → 6.5; Chemical 6.9 → 5.0; Biological 6.9 → 4.8	The decrease of the C with aging is expected to be due partly to the leaching of C-rich dissolved organic matter	Zeba et al. (2022)
Mixed hardwood biochar	450 °C	Eutric Cambisol	7 years, field experiment	Net TC loss: 5.8–6.5%	~0.8–0.9	–	–	Loss of biochar C is primarily by the process of solubilization and microbial degradation, despite partial sorption of external organic carbon	Williams et al. (2019)

* CDWs: chemical oxidation/dry–wet alternations; CFTs: chemical oxidation/freeze–thaw cycles

** Net TC change: reflects the combined effects of carbon loss and apparent enrichment during biochar aging and does not indicate true biochar mass gain

NA: Not available

$$Biochar\ Weathering = Function\ of\ Biochar, Soil, Climate, Burial\ Depth, Tillage, and\ Time$$

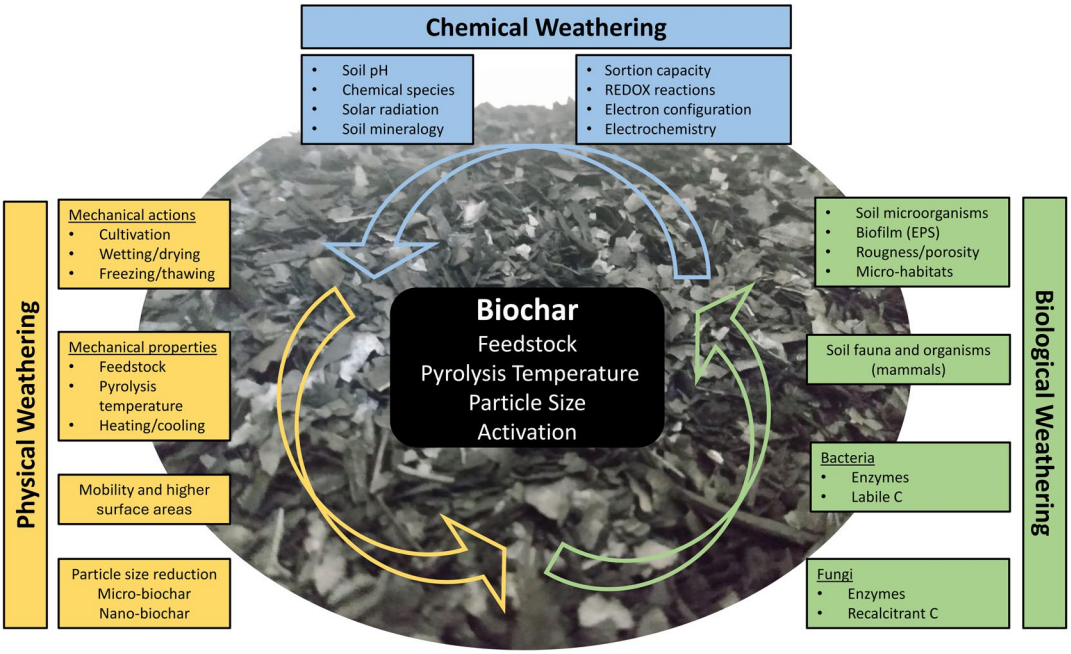


Fig. 2 Illustration of the various mechanisms responsible for biochar weathering reactions

Increasing pyrolysis temperatures of the same feedstock typically results in the smaller biochar sizes (Downie et al. 2009). As far as mechanical strength of the biochar, there is general consensus of reduced particle strength with increasing pyrolysis temperatures (Abreu Neto et al. 2018; Gurtner et al. 2023), while others have observed more significant dependency on feedstock than pyrolysis temperatures (Chrzazvez et al. 2014). Kumar et al. (1999) also determined that slower heating rates (< 4 °C min^{-1}) lead to improvements in compressive strength of the biochar particles. So, it is feasible that the different conclusions for the same pyrolysis temperatures can be observed solely due to the heating–cooling rates or feedstock differences. Overall, biochar mechanical properties are a complex relationship between feedstock properties (e.g., type, moisture content, particle size), pyrolysis temperature, heating/cooling rates, and thermal treatment duration that has yet to be fully elucidated (Byrne and Nagle 1997). Although attention has been focused on chemical and biological alterations, the mechanical crumbling of the biochar particles is also another critical process that needs to be fully understand, since this leads to loss of biochar C through particulate percolation, wind erosion, as well as surface runoff and potentially altering chemical and biological weathering. Thus, particle fragmentation resulting from physical weathering is a significant pathway for biochar transport from field applications.

3.2 Chemical weathering

Biochar tends to undergo chemical weathering due to the influence of moisture and oxygen in the soil. For example, surface oxidation of biochar results in the generation of additional carboxylic and phenolic groups (Wiedner et al. 2015; Williams et al. 2019; Zhong et al. 2020), thereby becoming more hydrophilic. Biochar interaction with soil minerals has been investigated for some time. Nguyen et al. (2008) observed elevated concentrations of Si and Al on the surface of charcoal residues from forest fires within 30 years of the fire event. Biochar specific studies have observed biochar–soil mineral interactions on more rapid time scales with some studies observing chemical interaction within 30 days (Lin et al. 2012). There have also been numerous studies on biochar's interaction with clay minerals (Yang et al. 2016; Jing et al. 2022; Du et al. 2023), which have also suggested a potential increase in biochar's durability due to the physical protection and pore filling by the clay minerals. Additionally, dissolved soil minerals can form organometallic complexes (Yang et al. 2016, 2018a), further expanding other potential chemical reaction pathways and mechanisms.

The overall conclusion to date from chemical weathering is that there are redistributions and re-equilibration of surface functional groups, manifesting itself in the formation of carboxyl groups and the subsequent disruption in the aromatic backbone structure with a strong dependency on the pyrolysis temperature (Shen et al.

2024). Biochar is also impacted by soil pH and the presence of chemical substances, especially oxidizing soil components such as manganese oxide (Tan et al. 2020, 2022). After UV exposure, biochar possesses increased surface area coupled with changes in the biochar's molecular composition with increases in the H- and O-containing acidic functional groups (Ellison et al. 2009; Liu et al. 2015a; Li et al. 2016; Rechberger et al. 2017; He et al. 2021). These photochemical alterations have resulted in significant increases in sorption capacity (Qin and Shin 2023). In addition to the bulk chemical compositional changes, there are also simultaneous alterations in the atomic electron configurations. Researchers have also hypothesized that UV exposure of biochar increases the free radicals on the biochar surface (Zhang et al. 2021a), while others have formulated the formation of triplet states on the surface of biochar, singlet oxygen species ($^1O_2$), as well as hydroxyl radicals being formed (Wan et al. 2021). Most of these new surface moieties have been postulated to be carboxylic acids (Rechberger et al. 2017), which would also reduce the net liming potential of biochar additions. Biocharweathering in soil has been observed to have varying impacts on the sorption of Cd in the soil, suggesting various biochar properties could also affect its weathering processes (Bandara et al. 2021).

3.3 Biological weathering

Soil microorganisms including bacteria and fungi play a vital role in the weathering of biochar. Particularly, the most labile C fractions in biochar, including volatile matter and aliphatic C structures, are subjected to initial weathering via microbial processes when biochar is first applied to soil (Morim et al. 2024). In addition to the direct mineralization of labile components on biochar, additional biological weathering occurs by the accumulation of extracellular enzymes on biochar's surface by soil microorganisms (i.e., biofilm formation), which can alter the performance of biochar in the environment. Biofilms are defined as a broad community of microorganisms, species of Gram-positive and/or Gram-negative bacteria, fungi, their associated microbial secretions (exopolysaccharides and enzymes), which grows attached to a surface depending on environmental conditions such as nutrient availability and microhabitat (Paul et al. 2024).

Biochar may interact with soil components, for example, soil minerals and microbial communities, influencing the mineralization of labile organic compounds for microbial growth and affecting the soluble organic matter in the soil (Graber et al. 2010). In general, it is assumed that wood-based biochars are more advantageous for microbially interactions, since they typically possess a high pore volume and have properly sized pores for providing micro-habitats for the soil microbiome (Graber et al. 2010; Singh et al. 2010; Jaafar et al. 2014; Yang et al. 2020).

Fungi and bacteria both can degrade the C-based surfaces of biochar, although at a very slow rate (Ascough et al. 2011; Liu et al. 2015b). Microbes can also directly utilize nutrients that are precipitated or sorbed on the biochar surface as well (Lehmann et al. 2011; Jaafar et al. 2014; Ralebitso-Senior and Orr 2016). The biochar surfaces are gradually oxidized with enzymes from soil microorganisms or root exudates, changing the biochar surfaces and soil fertility simultaneously (Mierzwa-Hersztek et al. 2019). The increase of biochar-induced microbiological activity is generally greater in the acidic and sandy textured soils (Li et al. 2020; Tsolis and Barouchas 2023). Microbial succession is a dynamic, multi-stage process where different microbial communities colonize the biochar surface, driven primarily by the changing physicochemical properties of the biochar and the surrounding soil environment over time during the weathering process (Kerner et al. 2023). The microbial succession process tends to shifts from communities that utilize easily available resources to those that break down more recalcitrant compounds with increasing time during the weathering process. The microbial succession include three stages: (i) initial early colonisation phase involving copiotrophic bacteria (e.g., Firmicutes, Bacteroidetes, Proteobacteria) consuming readily available C and nutrient sources; (ii) intermediate phase involving oligotrophic bacteria (e.g., Acidobacteria, Gemmatimonadetes) and saprophytic fungi which are better adapted to utilizing the remaining, more stable and recalcitrant aromatic C structures; and (iii) long-term stabilization phase involving primarily fungi leading to slow degradation of the highly recalcitrant biochar matrix over extended periods.

3.4 Interactions amongst weathering process

Physical, chemical and biological weathering processes act independently and collectively in affecting biochar properties in soil under natural conditions (Zhu et al. 2025; Williams et al. 2019). For example, while the breakdown of biochar into macroparticles is initiated by physical weathering processes involving mechanical actions, subsequent breakdown into micro- and nano-particles is accelerated by chemical and biological weathering processes involving dissolved soil elements and microorganisms. Physical encapsulation and coating of the biochar particles by soil minerals improves the durability of the biochar against microbial, physical and chemical weathering (Joseph et al. 2017; Chen et al. 2021a). Additionally, plant roots are an important redox interface (Geigenberger and Fernie 2014) that could promote the additional chemical weathering of biochar (Joseph et al.

2015). Solar radiation, especially ultraviolet (UV) radiation, plays an important role in the chemical degradation of biochar, and these photoreactions also can accelerate biological weathering. Biochar has been observed to alter the formation of biofilms in amended soils (Yan et al. 2023). Compared to smooth surfaces, rough and porous surfaces are more likely to adhere bacteria and form biofilms because of the enhanced contact surface and increased surface reactivity (Wang et al. 2024). The physical characteristics of surface area and pore diameter are very important for determining the suitability of the biochar for protecting soil microorganisms and providing opportunities for microbial interactions.

4 Factors affecting biochar weathering

The weathering of biochar in soil is influenced by a number of factors that include the nature of biochar, environmental conditions, and cultivation practices (Rahim et al. 2023; Long et al. 2024).

4.1 Nature of biochar

The inherent composition of the feedstock significantly impacts the biochar weathering. Woody biochar generally exhibits greater structural persistence due to its lignocellulosic origin, which favors the formation of condensed aromatic frameworks during pyrolysis (Spokas 2010; Chen et al. 2022a; Wang et al. 2022a). In addition, woody biochar may maintain its integrity longer than biochar from softer organic residues, highlighting the role of feedstock composition in determining physical weathering (Bandara et al. 2022) as the breakdown of macro into finer structures alters the distribution of reactive sites, influencing biochar persistence in the soil (Pan et al. 2021). In contrast, biochars derived from manure, sludge and other organic residues contain substantial mineral fractions that enhance their initial reactivity but contribute to accelerated leaching and structural fragmentation over time (Pan et al. 2021; Siatecka et al. 2021). For instance, chicken manure biochar exhibited greater weathering compared to wheat straw biochar, which was attributed to the weathering-induced increase in oxygenated functional groups on the biochar surface, destruction of porous structures, and release of dissolved organic C from weathered biochar (Yang et al. 2023). On the other hand, Mukherjee et al. (2014) demonstrated that while pyrolysis temperature has a relatively low effect on cation exchange capacity (CEC) changes during weathering, feedstock composition plays a more dominant role. Biochars derived from lignocellulosic materials, such as wood, exhibited lower increases in CEC compared to those derived from grasses, which experienced a much more pronounced rise in cation exchange properties (Fig. 3).

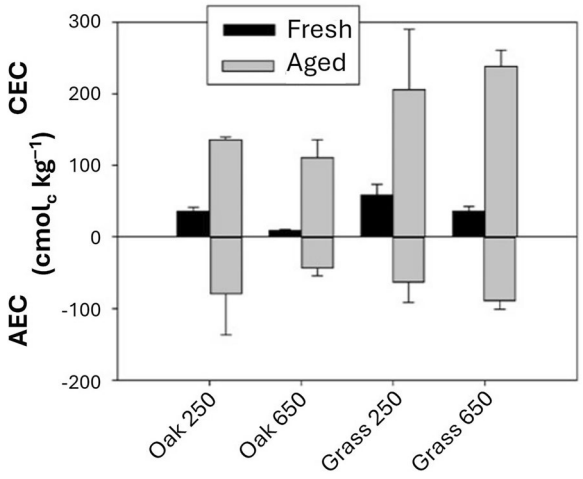


Fig. 3 Cation and anion exchange capacities (CEC and AEC, respectively) measured at pH 6–7 on fresh and "aged" oak and grass biochars produced at 250 and 650 °C (Mukherjee et al. 2014)

As biochar CEC is derived mainly from the presence of surface functional sites such as carboxylic or phenolic groups (Mia et al. 2017), this suggests that the initial organic composition of biochar determines the extent of oxidative functionalization over time, influencing its ability to retain nutrients and contaminants in soil.

Weathering-induced oxidation leads to a progressive increase in oxygen-containing functional groups, particularly carboxyl and carbonyl moieties, which modify the surface charge properties of biochar. These modifications enhance its affinity for metal cations but also reduce its hydrophobicity and stability in aqueous environments (Rechberger et al. 2017; Bandara et al. 2022). High-ash biochars undergo preferential ion exchange, leading to a reduction in their sorptive capacity over time (Siatecka and Oleszczuk 2022). Structural disruptions, facilitated by mineral dissolution, further compromise the integrity of biochar matrices, making them more susceptible to microbial and abiotic degradation (Yang et al. 2016). The presence of aromatic and quinoid groups in biochar enhances its reactivity and can accelerate the oxidation of minerals (Wang et al. 2020a). Microbial degradation is initiated by the breakdown of aliphatic C compounds, which results in the disconnection of aromatic moieties and oxidation at the break points (Mia et al. 2017). In addition, the C bioavailability of biochar determines the speed of microbial colonization (Quilliam et al. 2013). Overall, the rate of microbial colonization increases with the labile C content (e.g., aliphatic C compounds) (Gorovtsov et al. 2020). After short-term mineralization of the labile C pool, the degradation rate of biochar C decreases dramatically (Kuzyakov et al. 2009; Ameloot et al. 2013).

4.2 Soil properties

The long-term stability of biochar in soils is influenced by a range of soil properties and soil types (Fang et al. 2014a). pH, texture, mineral composition, redox potential, and microbial communities interact with biochar, altering its surface chemistry, structural integrity, and longevity.

4.2.1 Soil pH/redox conditions

Studies have demonstrated that soil pH plays a crucial role in determining the oxidation and dissolution rates of biochar. In acidic soils, biochar undergoes accelerated oxidation due to increased protonation of surface functional groups, leading to enhanced leaching of labile organic compounds and associated mineral elements (Rechberger et al. 2017). However, acidic soils or soil acidification can promote mineral dissolution from biochar, leading to the release of mineral components as well as adsorbed nutrients and metals, a reduction in ash content, and an increase in acidity levels (Houben et al. 2013; Zhang et al. 2025a, b). Studies in acidic soils have, for instance, shown that after 13 years of weathering, biochar pH values can decrease from 7.4 to around 6.8 (Apostolović et al. 2024). Conversely, alkaline soils such as calcareous soils, which contain high carbonate concentrations, might further contribute to biochar stabilization.

Redox conditions in soil further regulate biochar oxidation, affecting its aromaticity and functional group distribution. Under well-aerated conditions, biochar oxidation is intensified, leading to the formation of carboxyl and carbonyl groups, which increase its hydrophilicity and interaction with dissolved organic matter and nutrients (Yang et al. 2016). This transformation results in an increased affinity for water and enhanced adsorption of soil nutrients and may favor the transport of biochar colloids (Zhao and Shang 2023). Conversely, anaerobic conditions slow down oxidative stress, preserving the structural integrity of biochar over extended periods (Wu et al. 2016). These alternating redox cycles can lead to complex transformations in biochar's chemical structure, including shifts in functional groups and changes in mineral-organic associations, which may in turn influence its stability (Nguyen and Lehmann 2009). High soil moisture also facilitates the dissolution and leaching of biochar-derived dissolved organic C, which contributes to the loss of biochar mass over time (Williams et al. 2019). Eventually, soil moisture content plays a key role on biochar weathering through its impact on biological activity, as wetter soils facilitate microbial colonization of biochar surfaces, leading potentially to increased mineralization of labile biochar components (Rombolà et al. 2023). In contrast, drier soils slow down microbial degradation, but may promote abiotic oxidation processes, particularly in surface soils where photochemical reactions can occur (Sorrenti et al. 2016).

4.2.2 Soil texture/mineralogy

Soil texture also has a significant impact on biochar weathering. Clay-rich soils enhance biochar stability by physically encapsulating biochar particles, reducing their exposure to oxidative agents and microbial degradation (Nguyen et al. 2008). Additionally, interactions between biochar and clay minerals, particularly the formation of organo-mineral associations, have been shown to enhance biochar stability by limiting microbial access and preventing biochar from environmental degradation (Qian and Chen 2014). For instance, Bolan et al. (2012) and Yang et al. (2022a) found that the positive effect of clay on biochar stability led to lower C mineralization rates compared to sandy soils. Sandy soils, in contrast, promote fragmentation and redistribution due to lower cohesion and higher permeability, leading to faster degradation of biochar structures (de la Rosa et al. 2018; Pei et al. 2021). Mukherjee et al. (2014) further demonstrated that biochar weathering varies with soil type, with sandy soils promoting faster mineralization and clayey soils fostering long-term stabilization through mineral sorption and physical protection.

Soil minerals contribute to biochar stabilization by adsorbing onto its surfaces and protecting it from weathering (Nguyen et al. 2008; Lin et al. 2012). Kaolinite, montmorillonite, Fe oxides, and Al oxides can bind strongly to biochar surfaces through the formation of surface complexes such as Fe–O–C or by deposition into inner pores. This results in pore clogging and enhanced oxidation resistance (Yang et al. 2016; Ren et al. 2018; Jing et al. 2022). High concentrations of Al have been observed at the interface between soil minerals and weathered biochars, highlighting the crucial role of Al-containing minerals in biochar stability (Lin et al. 2012). Biochar readily adsorbs elements such as Al, Fe, and Ca, forming stable complexes with minerals that enhance its recalcitrance (Qian and Chen 2014; Yang et al. 2018a). These mineral interactions contribute also to the physical stabilization of biochar by forming a protective layer that prevents further oxidation (Yang et al. 2018b). However, mineral protection mechanisms are dynamic, with continuous adsorption–desorption processes modifying biochar structure and stability over time. This insight suggests that biochar stability assessments should account for evolving biochar–mineral interactions, rather than treating them as static properties (Wang et al. 2022a).

4.2.3 Soil microbial community

Microbial communities also play a fundamental role in biochar weathering through enzymatic oxidation and co-metabolism with soil organic matter (Quan et al. 2020a). In soils with high microbial diversity, biochar experiences enhanced biotic weathering, leading to changes in pore structure and surface chemistry (Bandara et al. 2022). Actinobacteria and fungi are particularly influential in biochar degradation, as they produce oxidative enzymes that break down its aromatic components (Zimmermann et al. 2012). The extent of microbial-induced biochar weathering is largely dependent on soil organic matter content, nutrient availability, and moisture levels (Pan et al. 2021). Wang et al. (2022b) argue that microbial colonization of biochar is not a one-time event but a continuous process, with microbial communities evolving in response to biochar transformations. This underscores the need for long-term studies to capture the full extent of microbial impacts on biochar weathering.

Soil organic matter interactions further modulate biochar weathering by affecting its interaction with soil minerals and microbial populations. High soil organic matter content has been found to enhance biochar stability by forming protective coatings that limit oxidation and microbial degradation (Lin et al. 2012; Qian and Chen 2014). The degree of these interactions varies among soil types, with organic-rich soils exhibiting stronger biochar–organic matter associations compared to mineral-dominated soils (Pan et al. 2021). Soil organic matter can also contribute to the stabilization of biochar during weathering. Studies have shown that biochar weathered in the presence of humic substances exhibited increased aromaticity and molecular weight, contributing to its persistence in the soil (Hammerschmiedt et al. 2021; Yue et al. 2023).

4.3 Climate conditions

Climate conditions, especially temperature and rainfall, have a strong impact on biochar weathering. Elevated temperatures can accelerate biochar weathering through higher microbial activity and chemical oxidation, affecting its stability and reactivity in soil (Fang et al. 2014b; Williams et al. 2019). Freeze–thaw cycles, common in temperate climates, also contribute to biochar breakdown because expansion and shrinkage of water molecules induce physical fragmentation and exposing new reactive surfaces to microbial and chemical weathering (Tan et al. 2020; Kim et al. 2021). Seasonal wet-dry cycles may have similar effects on biochar weathering by promoting its physical disintegration (Aubertin et al. 2021). During rainfall events, water sorbed in biochar can cause also graphite sheets to swell, resulting in structural expansion, contributing to physical weathering of biochar (Spokas et al. 2014; Tan et al. 2020). Rainfall events can also promote biochar oxidation due to the direct interaction with dissolved oxygen and nitrogen oxides in rainwater (Feng et al. 2018; Rombolà et al. 2023). Moreover, heavy rainfall can lead to the dissolution and transport of biochar-derived dissolved organic C, reducing biochar stability in the soil and potentially and further modifying biochar surface chemistry (Liu and Chen 2022). Conversely, arid conditions may enhance biochar persistence by limiting microbial activity and water-mediated oxidation reactions (Paetsch et al. 2018).

Light exposure, particularly ultraviolet (UV) radiation, can accelerate biochar weathering by promoting surface oxidation and altering its chemical composition (Qin and Shin 2023). Dissolved C released by biochar is susceptible to photo-transformation (Fu et al. 2016) and this effect might particularly be relevant in regions with high solar radiation, where biochar may undergo more rapid structural and compositional changes. Photocatalytic weathering is another key process affecting biochar stability, particularly in environments with abundant light and reactive minerals. Recent studies have shown that photocatalytic reactions, particularly those involving Fe and organic acids, enhance the degradation of biochar through the production of hydroxyl radicals (Quan et al. 2020b). These radicals promote oxidation of biochar surface functional groups, increasing oxygen content and altering its adsorption and chemical properties.

Overall, the interplay between soil, climate and biochar characteristics drives its weathering and weathering dynamics. Soil pH, mineralogy, redox potential, microbial activity, and organic matter content collectively control biochar stability and functionality in soil systems which are in the meantime driven by climate conditions. As a result, a comprehensive understanding of these processes and their interaction would facilitate optimized biochar applications for sustainable soil management.

4.4 Cultivation practices

The role of cultivation practices in biochar weathering is a critical aspect influencing its stability and effectiveness in soil applications. Various agricultural practices, including tillage, crop rotation, irrigation, and fertilization, interact with biochar and modify its physical and chemical properties over time (Table 2). These interactions affect the longevity and functionality of biochar in soil systems, influencing its role in C sequestration, nutrient retention, and soil amendment efficiency.

4.4.1 Tillage practices

Tillage practices significantly impact biochar weathering by altering soil structure and aeration. Intensive tillage increases soil disturbance, exposing biochar to oxidative

Table 2 Impact of agricultural practices on biochar weathering with the main key involved process and supporting references

Agricultural practice	Impact	Key process	Reference
Tillage	+	Oxidation, formation of oxygen-containing functional groups (carboxyl, carbonyl) and mechanical fragmentation	Cheng et al. (2008), Hardy et al. (2017b), Rechberger et al. (2017), Zanutel and Bielders (2023)
No-tillage	–	Preserves biochar structural integrity (reduced fragmentation) and delays oxidation and microbial decomposition	Huang et al. (2024), Yang et al. (2016)
Organic amendments	+	Enhances microbial activity contributing to biochar aging via enzymatic degradation	Zimmerman and Ouyang (2019)
Compost addition	–	Reduction in fragmentation, protecting particles from excessive exposure to oxygen and fragmentation	Aubertin et al. (2021)
Fertilization (Nitrogen)	±	High nitrogen fertilization stimulates microbial decomposition of biochar via co-metabolism Low nitrogen fertilization stimulates the metabolism of fungi, resulting in higher biochar oxidation	Jiang et al. (2016), Šimanský et al. (2016) LeCroy et al. (2013)
Lime	–	Reduces weathering rates by buffering soil acidity and stabilizing biochar structure	Jiang et al. (2016), Hardy et al. (2017b), Zhang et al. (2021b)
Irrigation	+	Increases biochar's exposure to water, enhancing dissolution, higher biochar colloid transport, oxidation, and microbial colonization	Yang et al. (2016), Ma et al. (2019), Zhao and Shang (2024)
Excessive irrigation	–	Can preserve biochar by creating anaerobic conditions, slowing oxidative degradation	Wang et al. (2020a)
Crops	+	Higher microbial colonization, rhizosphere effects, including organic acid exudation and enzyme activity, biofilm formation	Houben and Sonnet (2015), Liu et al. (2017), Bertola et al. (2019), Li et al. (2019), Williams et al. (2019), Hua et al. (2020), Honvault et al. (2022)

and microbial degradation. The increased oxygen availability promotes oxidation, leading to the formation of oxygen-containing functional groups such as carboxyl and carbonyl moieties, which enhance biochar hydrophilicity and its interaction with soil minerals and organic matter (Rechberger et al. 2017; Siatecka et al. 2021). As reported by Hardy et al. (2017a), cultivation practices play a significant role in biochar weathering. The authors compared H:C and O:C ratios of charcoal particles extracted from preindustrial kilns in Wallonia, Belgium, along a chronosequence of land use change from forest to agricultural soil. They showed that the oxidation of charcoal particles was much more pronounced in samples taken from long-term cropland soil than from forest soil (Fig. 4), even though charcoal was incorporated at the same time in these soils. This indicates that long-term soil cultivation can increase biochar weathering, likely due to intensive tillage which increases biochar surface area and promotes biochar oxidation leading to the creation of phenol, carbonyl and carboxyl functionalities at the edge of aromatic rings (Cheng et al. 2008; Wang et al. 2020a). Moreover, tillage accelerates mechanical fragmentation, breaking down biochar particles into finer fractions, which can increase their reactivity but also their susceptibility to particulate percolation (Hardy et al. 2017a; Zanutel and Bielders 2023). The impact of tillage on biochar fragmentation might potentially be mitigated by the addition of compost. Indeed, Aubertin et al. (2021) have shown that compost addition could reduce biochar fragmentation and mass loss during weathering, likely by protecting biochar particles from excessive exposure to oxygen and mechanical disruption. This suggests that in tilled soils, biochar may persist longer when co-applied with compost, as the organic matrix provides a buffering effect against rapid degradation.

Long-term evidence from pre-industrial charcoal kiln sites shows that biochar particles persist for over 150 years in agricultural soils, even under continuous cultivation, despite mechanical disturbance gradually dispersing biochar throughout the soil profile (Hardy et al. 2016, 2017a). In contrast, no-till systems minimize soil disturbance, thereby preserving biochar structural integrity and delaying oxidation and microbial decomposition. Studies have shown that biochar persists longer under no-till conditions, as the reduced disturbance minimizes fragmentation and maintains its structural integrity over time (Yang et al. 2016).

4.4.2 Irrigation practices

Irrigation regimes play a crucial role in biochar weathering by influencing moisture dynamics and redox conditions. Water infiltration enhances biochar interactions with soil minerals, potentially leading to the formation of stable organo-mineral complexes that protect biochar from oxidation (Lin et al. 2012). Frequent irrigation increases biochar exposure to water, which enhances

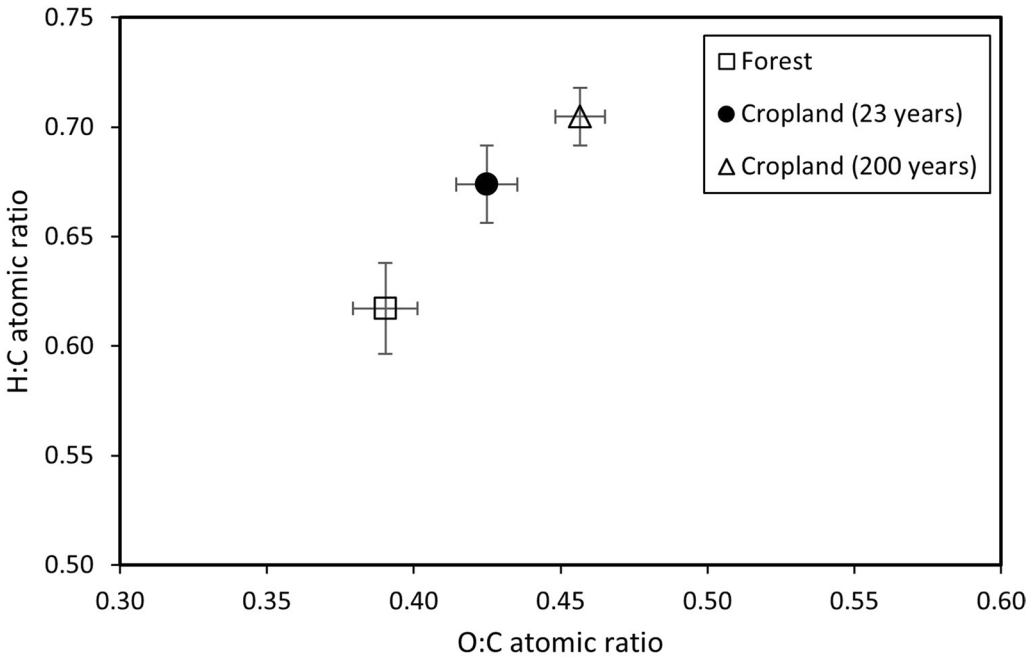


Fig. 4 Charcoal from preindustrial kilns in Wallonia (Belgium) plotted in a Van Krevelen diagram (organic H:C atomic ratio vs. organic O:C atomic ratio). Samples were collected in a forest soil, a soil under cropland for 23 years and a soil under cropland for 200 years (data from Hardy et al. 2017b)

dissolution and leaching of labile organic and inorganic compounds as well as colloids (Ma et al. 2019; Zhao and Shang 2024). In highly irrigated systems, biochar undergoes hydration, leading to increased surface oxidation and microbial colonization (Yang et al. 2016). However, excessive irrigation or waterlogging could create anaerobic conditions, which slow down oxidative degradation and preserve biochar stability (Wang et al. 2020a). In contrast, dryland farming systems where irrigation is limited may result in longer biochar persistence due to reduced microbial activity and oxidation rates (Sorrenti et al. 2016). The interplay between moisture availability and biochar stability highlights the importance of irrigation management in agricultural systems.

4.4.3 Fertilization practices

Fertilization practices influence biochar weathering by modifying soil pH, microbial activity, and nutrient dynamics. Low nitrogen fertilization was found to stimulate the metabolism of mycorrhizal fungi, driving the hyphae to more actively seek nutrients, resulting in more extensive oxidation of biochar via extracellular co-metabolism (LeCroy et al. 2013). On the other hand, increased nitrogen availability stimulates microbial decomposition of soil organic matter, which can enhance biochar mineralization through co-metabolism effects (Jiang et al. 2016; Šimanský et al. 2016; de la Rosa et al. 2018). Nitrogen fertilization using ammonium-based fertilizers is known to promote soil acidification, which could in turn accelerate biochar weathering due to protonation of the functional groups and ash dissolution (Al-Rabaiai et al. 2024; Zhang et al. 2025a, b). Acid-induced weathering of biochar might potentially be counteracted by applying biochar along with lime or alkaline fertilizers, which would reduce oxidation rates by buffering soil acidity and stabilizing the biochar structure (Jiang et al. 2016; Hardy et al. 2017b; Zhang et al. 2021b). Organic amendments, such as compost or manure, contribute to biochar weathering by boosting microbial activity and enzymatic degradation, resulting in gradual changes to its physicochemical properties (Zimmerman and Ouyang 2019).

4.4.4 Crop rotation

Crop rotation and plant root interactions also contribute to biochar weathering through rhizosphere effects in relation to release of root exudates and microbial community association. Plant roots exude organic acids, enzymes, and other metabolites that interact with biochar surfaces, altering their chemical composition and mineral associations. These root exudates from different crops enhance the dissolution of biochar-derived nutrients (Houben and Sonnet 2015; Honvault et al. 2022). Some exudates contain organic acids that accelerate biochar oxidation, while others contribute to the formation of protective coatings that enhance its persistence (Liu et al. 2017; Li et al. 2019). Furthermore, the microbial

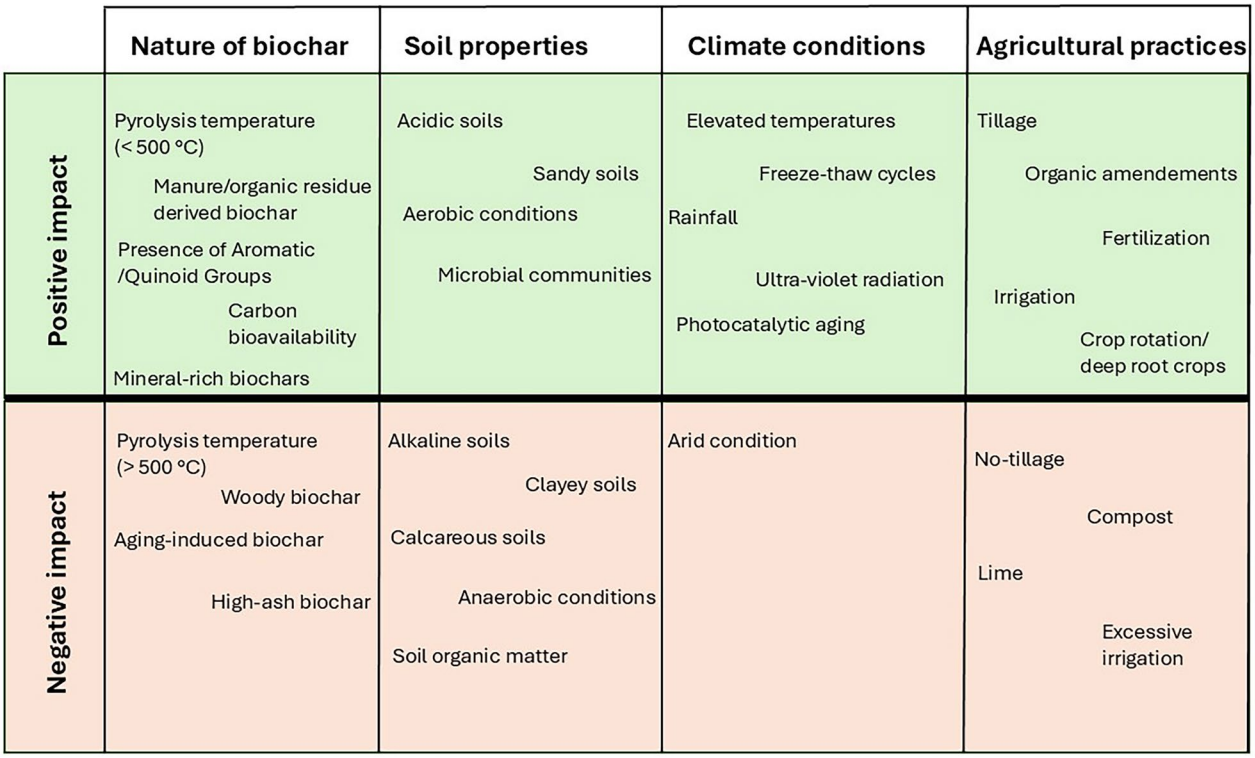


Fig. 5 Impact of nature of biochar, soil properties, climate conditions, and agricultural practices on biochar weathering

communities associated with plant roots play a role in biochar degradation by facilitating enzymatic oxidation and co-metabolism with soil organic matter (Williams et al. 2019; Hua et al. 2020). Different crop species influence biochar weathering to varying degrees, with deep-rooted plants and legumes which are expected to promote more extensive interactions due to their root exudation patterns and symbiotic microbial associations (LeCroy et al. 2013). The composition of soil microbial communities also plays a crucial role in biochar weathering. Certain plant species promote the colonization of biochar surfaces by fungi and bacteria, leading to biofilm formation and potentially increased decomposition (Bertola et al. 2019). Overall, root-microorganism interactions and environmental factors, such as temperature and precipitation, should be further considered when assessing biochar longevity in agricultural soils.

In short, Fig. 5 presents a conceptual framework categorizing the positive/negative impact of the nature of biochar, soil properties, climate conditions, and agricultural practices on biochar weathering. Concerning the impact of pyrolysis temperature and feedstock of biochar in its weathering, we were able to conclude that pyrolysis temperature lower than 500 °C, manure/organic residue derived biochar, presence of aromatic or quinoid groups, C availability and mineral-rich biochar accelerate biochar weathering, which is attributed to the higher level of dissolved and volatile organic compounds in biochar produced below 500 °C than those produced at higher temperatures (Soares et al. 2022). On the other hand, pyrolysis temperature higher than 500 °C, wood-derived biochar, weathering-induced biochar, and high-ash biochar contributed to enhanced biochar stabilization. The types of soils that favored biochar weathering were acidic and sandy soils, especially under aerobic conditions. In contrast, calcareous, alkaline, or clayey soil reduced biochar weathering, especially soil with elevated organic matter or under anaerobic conditions. According to our review, only arid conditions contributed negatively to the biochar weathering, while elevated temperature, freeze–thaw cycles, rainfall, ultraviolet radiation, and photocatalytic radiation stimulated this process. Regarding the impact of agricultural practices on biochar weathering, we were able to identify a positive impact of tillage, organic amendments, fertilization, irrigation, and legumes/deep-rooted crops. A negative impact of no-tillage, compost, lime, and excessive irrigation on biochar weathering was observed.

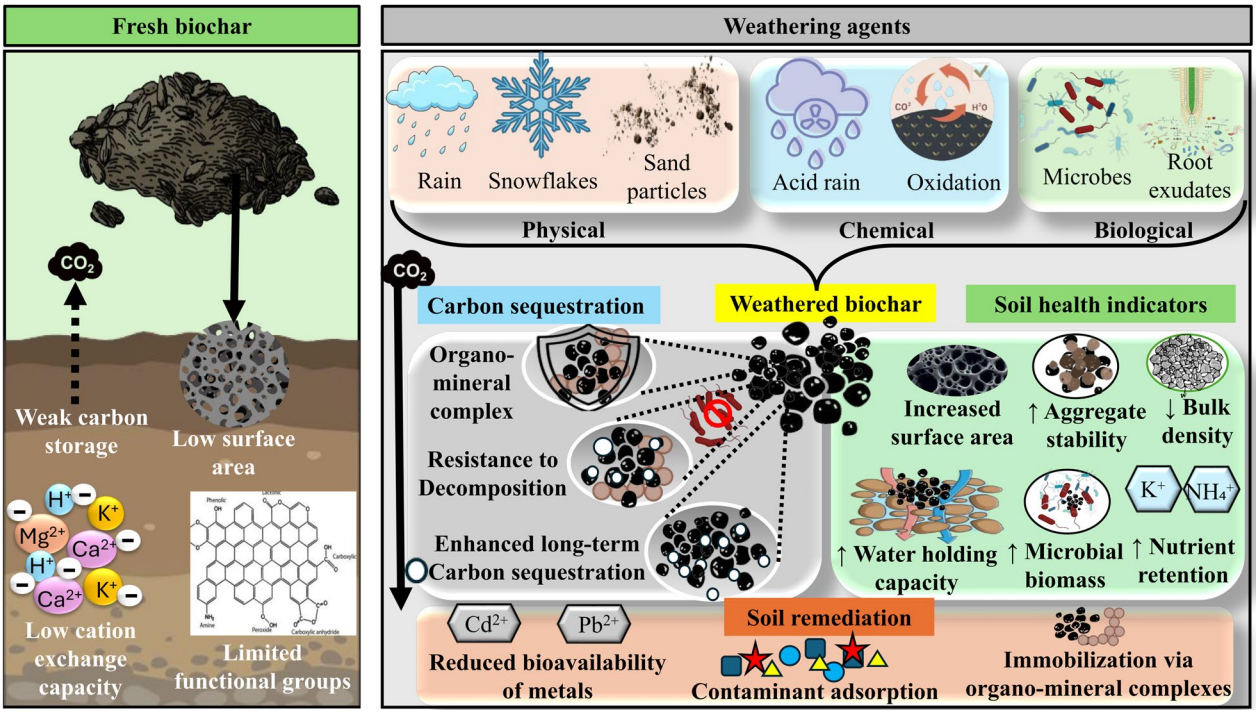


Fig. 6 Schematic diagram illustrating the effect of biochar weathering on carbon sequestration and soil remediation

5 Implications of biochar weathering

The weathering-initiated changes in biochar are likely to significantly alter the interactions between biochar and soil components, thereby impacting its soil health, C sequestration, and soil remediation benefits (Fig. 6).

5.1 Soil health

Biochar soil amendments improve soil properties in various ways (Schmidt et al. 2021). Numerous meta-analyses systematically reviewing case studies have demonstrated that biochar can enhance soil hydraulic properties (Omondi et al. 2016; Gao et al. 2020), microbial diversity and biomass (Zhu et al. 2017; Pokharel et al. 2020; Zhang et al. 2018; Xu et al. 2014), and soil organic C (Gross et al. 2021), contributing to a healthier and more productive soil ecosystem. However, these findings are often based on short-term observations, typically from laboratory or incubation experiments. The persistence of these benefits under real-world conditions, specifically how biochar weathering in soil affects physical and chemical properties over time, eventually affecting soil health, remains less understood.

5.1.1 Influence of biochar weathering on soil physical properties

During weathering after soil application, biochar particles are exposed to abiotic and biotic processes that oxidize and modify both the internal structure and surface chemistry of the material. These physical and chemical transformations significantly influence biochar's capacity to affect soil health. Weathering alters biochar's porosity, which is a key factor in its impact on soil properties (Dong et al. 2017). When added to soil, the porous nature of biochar affects soil porosity with both positive and negative implications for soil hydraulics. Fresh biochar often contains a high proportion of micropores, particularly when produced from fine sized biomass material and at very high pyrolysis temperatures (≥700 °C) (Muzyka et al. 2023; Zhang et al. 2015a, b; Liu et al. 2018). Water trapped in these pores is not plant-available; thus, fresh addition of microporous biochar can intensify plant water stress reactions. During weathering, biochar can sorb various organic and inorganic substances, forming coatings that block pores, thereby limiting gas exchange, water infiltration, and the retention of dissolved nutrients (Pignatello et al. 2024). However, these coated particles contribute to soil aggregation, promoting mesoporous structures and improving hydraulic conditions (Hagemann et al. 2017). Enhanced aggregation also increases soil stability, reduces erosion and runoff, and supports root growth and microbial habitats (Sarker et al. 2022).

5.1.2 Influence of biochar weathering on soil chemical properties

As biochar weathers, surface oxidation leads to the formation of O-containing functional groups that improve nutrient retention and exchange (Pignatello et al. 2024). Fresh biochar surfaces often have hydrophobic properties, and weathering promotes hydrophilicity of biochar, with positive implications for the plant-available water holding capacity. These chemical changes sustain nutrient availability, supporting long-term soil fertility and crop productivity (Atkinson et al. 2010). For instance, biochar-amended soils have demonstrated improved plant growth even 13 years after application, with increased nitrogen and phosphorus uptake (Apostolović et al. 2024). This was attributed to the persistence of certain beneficial soil chemical properties, such as ammonium retention and elevated soil C content. Although some initial effects like pH increase, electrical conductivity, and enhanced surface area decline over time, weathered biochar has been associated with greater availability of plant-available ammonium and soluble phosphorus (Fig. 7), enhancing plant growth.

5.1.3 Co-composted biochar as a strategy to accelerate weathering

Co-composted biochar has shown the highest long-term positive impact on soil physicochemical properties and plant productivity (Apostolović et al. 2024). During co-composting, biochar particles undergo oxidation and sorb nutrients released from the microbial mineralization of compost. The organic coatings formed during co-composting resemble those developed during long-term weathering, suggesting that co-composting mimics and accelerates these natural processes. These coatings have a chemical composition similar to the parent compost, including plant-available water, mineralized nitrogen compounds, and phosphorus (Hagemann et al. 2017). Because these nutrients are slowly released, co-composted biochar can sustain fertility and productivity over time. Moreover, it was demonstrated that the plants grown on soils amended with weathered co-composted biochar used water more efficiently in the long term, compared to fresh biochar and weathered pure biochar (Apostolović et al. 2024).

In summary, biochar weathering exerts a positive influence on soil health by enhancing nutrient retention and availability, thereby sustaining soil fertility over the long term (Atkinson et al. 2010). It also improves water retention, which increases the soil's resilience to drought and reduces irrigation demands (Razzaghi et al. 2020). Furthermore, weathered biochar contributes to better soil structure, including increased porosity and reduced bulk density, which benefits root development and microbial activity (Apostolović et al. 2024). In addition, it supports reduced soil erosion and improved aggregation, helping to preserve topsoil and mitigate land degradation (Sarker et al. 2022). However, the effects of biochar weathering are influenced by several factors, such as the type of biochar, soil characteristics, climate conditions, and application rates (Pignatello et al. 2024). While most studies highlight positive outcomes, variability in results across different environments underscores the importance of site-specific management and the need for further long-term field research.

5.2 Carbon sequestration

The C sequestration potential of biochar is a key reason that it has become one of the most widely adopted carbon dioxide (CO_2) removal strategies, with the highest sales and deliveries among CO_2removal methods (Zhang et al. 2025a, b). Its global potential is estimated between 2.7 and 10.3 Gt CO_2 per year, equating to 6–22% of the 3,300 Gt CO_2 that the IPCC projects will be emitted by the end of the century (Moinet et al. 2023). The core mechanism behind this sequestration lies in pyrolysis: during the process, the organic macromolecular structures of biomass are converted into stable, fused aromatic rings, resulting in a highly recalcitrant material. Consequently, biochar has significantly lower mineralization rates than the original biomass. Its long-term stability is often linked to its H/C ratio, an indicator of aromaticity (Ippolito et al. 2020). Biochars with H/C ratios below 0.2 are estimated to lose less than 5% of their mass over 100 years (Budai et al. 2013). However, the C sequestration potential of biochar in soil is influenced by weathering processes that affect the material's fate over time. These include dissipation pathways such as mineralization, microbial metabolization, and translocation (both vertical and lateral).

Biochar mineralization rates depend on a combination of biological, physical, and chemical factors in the soil, as well as the feedstock and pyrolysis parameters used during production (Lehmann et al. 2024). As biochar weathers in soil, its properties change: oxygen-containing functional groups increase, while C and nitrogen contents decrease, all of which influence its degradation dynamics and C sequestration potential. Initially, labile (mostly aliphatic) fractions are preferentially mineralized due to their weaker C-bonds which require lower activation energy (Rudra et al. 2024). Over time, the remaining stable, aromatic fraction becomes less accessible to microbial decomposition, requiring more specialized microbial communities capable of breaking down the "aromatic backbone", a process that occurs over extended timeframes (Wang et al. 2016).

Besides the degradation of the biochar particles, the C sequestration potential of biochar-amended soils is also

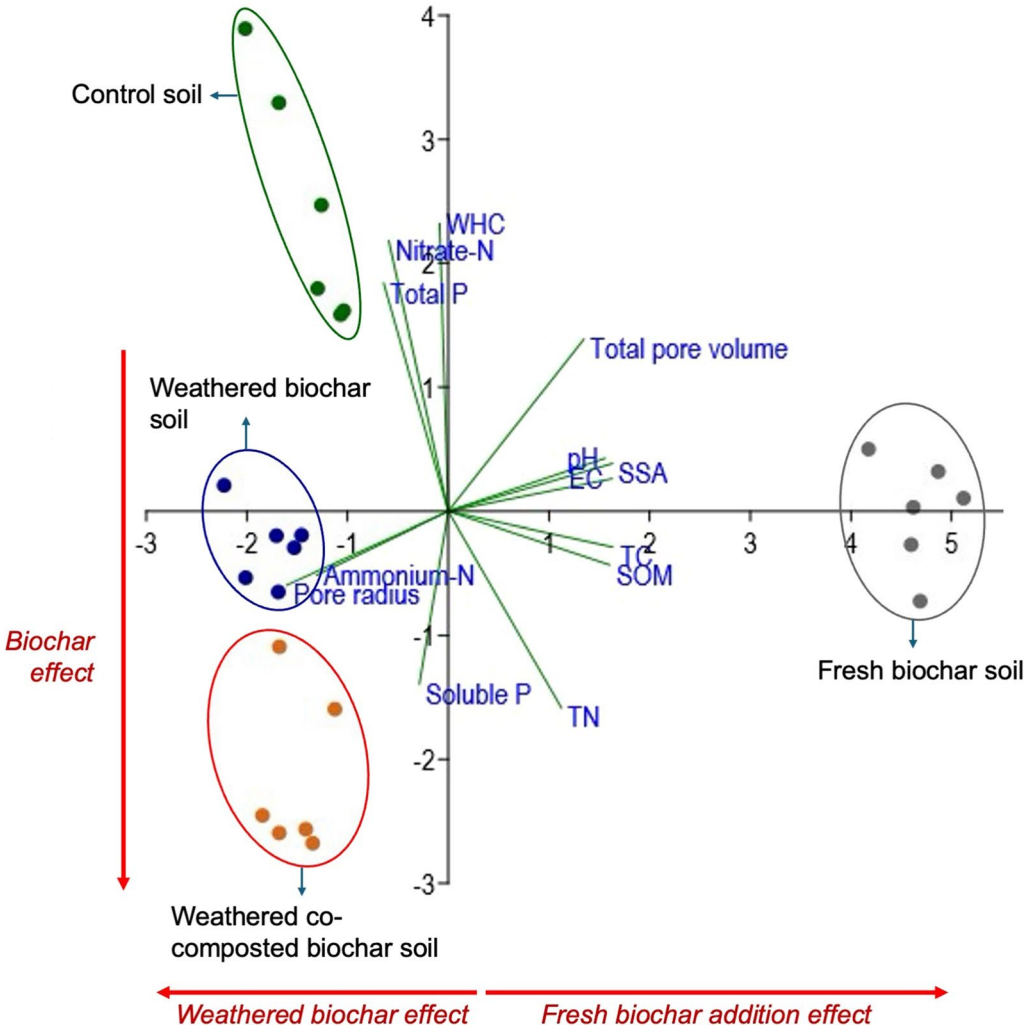


Fig. 7 Principal component analysis (PCA) biplot of soil properties after 13 years of biochar weathering (data from Apostolović et al. 2024). Treatments include: Control (unamended soil), Weathered biochar soil, Fresh biochar soil, and Weathered co-composted biochar soil. PC2 (ordinate) shows a clear biochar effect, separating all biochar-amended soils from the control. PC1 (abscissa) distinguishes fresh biochar addition effects from weathered biochar effects. Vectors indicate the contribution of individual soil variables to each principal component

influenced by biochar's effect on native soil organic matter (Fig. 8). Numerous studies have reported a stabilizing effect on soil organic matter over time, referred to as "negative priming", where reduced mineralization leads to greater net C storage (Wang et al. 2016). However, the priming effect varies widely due to complex interactions among soil biotic and abiotic factors, plant growth, and biochar characteristics (Whitman et al. 2024). Some systems exhibit "positive priming," where biochar addition enhances soil organic matter mineralization. This may result from improved microbial activity driven by changes in pH, immobilization of inhibitory compounds, or the presence of labile C from the biochar itself (Zimmerman and Ouyang 2019). Conversely, negative priming is often associated with microbial limitations due to nutrient immobilization, sorption effects, or unsuitable pH conditions (Maestrini et al. 2014; Wang et al. 2016). These dynamics are not static and can shift over time, often transitioning from positive to negative priming due to microbial community adaptations and biochar weathering. During weathering, biochar can directly stabilize soil organic matter on its surface, partly due to its strong affinity for organic compounds (Liang et al. 2006). Therefore, weathered and or co-composted particles often develop coatings rich in C and nutrients, which both protect soil organic matter from degradation and protect the "aromatic backbone" from microbial access (Hagemann et al. 2017).

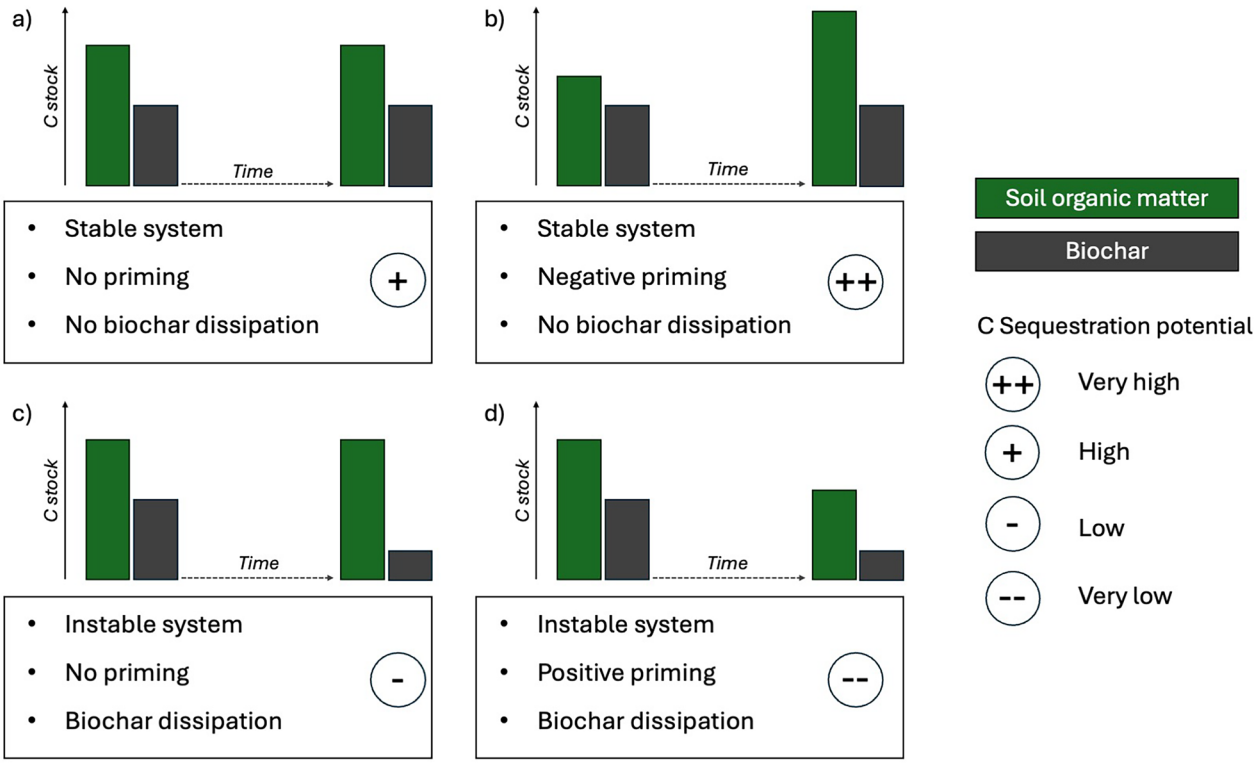


Fig. 8 Conceptual overview of four scenarios (**a**–**d**) illustrating potential temporal dynamics of soil organic matter (SOM) and biochar carbon stocks in biochar-amended soils and the resulting implications for carbon (C) sequestration potential. Scenarios (**a**) and (**b**) represent stable systems with no or negative SOM priming and negligible biochar loss, leading to high or very high C sequestration potential. Scenarios (**c**) and (**d**) represent unstable systems with no or positive SOM priming and biochar dissipation, resulting in low or very low C sequestration potential

Microbial metabolization of biochar is a relatively overlooked dissipation pathway, mainly because the degradation occurs at such low rates that mass losses and transformation products are difficult to detect within the typical duration of research studies. Nevertheless, research on microbial black carbon metabolites has shown that they are as widespread as their parent material and more abundant in acidic or tropical soils (Haumaier 2010; Di Rauso Simeone et al. 2018). In a recent long-term field experiment, metabolites were detected three and eleven years after biochar application, with stocks increasing slightly over time (Gross et al. 2025). However, the metabolite stocks comprised less than 1% of total detectable black carbon, indicating a minor role in biochar dissipation.

Vertical and lateral biochar translocation is the major driver of biochar dissipation. Vertical movement varies with factors such as precipitation, tillage, bioturbation, and soil texture. For example, in a sandy soil, 50% of applied biochar was found below 30 cm within 4 years (Haefele et al. 2011), while Obia et al. (2017) observed only 9–19% vertical transport in a loamy soil. Lateral transport, driven by erosion, tillage, water flow, and bioturbation, can account for 20–53% of total biochar loss (Major et al. 2010; Rumpel 2024). In long-term field experiments in Northern and Southern Germany, biochar dissipation varied between sandy and loamy soils over 9–11 years, with higher dissipation in sandy soils (Gross et al. 2024). Weathering-induced disintegration of biochar particles increases particle mobility through the soil pore systems, especially in the form of biochar colloids. The macro-, micro-, and nano-sized biochar particles resulting from physical disintegration are readily suspended in the soil solution and moved by infiltration and colloidal transport, thereby resulting in the loss of C and impacting biochar-induced C sequestration in soil (Yang et al. 2020). For example, based on data collected from both artificially and field (naturally) weathered biochar, Spokas et al. (2014) suggested that physical breakdown of the biochar structure contributes to the loss of biochar through leaching and colloidal movement. Their study indicated that depending on the nature of biochar, the loss of biochar through physical breakdown ranged from 1% to 49% (w/w). Furthermore, these colloids exhibit distinct reactivity, influencing both nutrient availability and pollutant mobility (Yang et al. 2019).

Despite measurable dissipation, studies have shown that the aromatic core of biochar remains intact even after long-term field exposure. For instance, in the aforementioned field experiment in Northern Germany, the aromatic structure persisted 9 years after application in sandy soil; similar findings were reported in the loamy soil in Southern Germany after eleven years (Gross et al. 2024), and in a sandy clay loam in Wales thirteen years post-application (Brown et al. 2025). Furthermore, in the latter two sites, positive long-term effects of weathered biochar on soil organic matter were also observed, indicating negative priming.

More effective long-term C storage can be achieved in stable systems that maintain both stable biochar (i.e. no biochar dissipation) and native soil organic matter stocks (i.e. no priming or negative priming) (Fig. 8a and b). Unstable systems with high biochar dissipation rates are less effective (Fig. 8c and d). However, even weathered and translocated biochar has been shown to remain highly aromatic, indicating that the core biochar C sequestration mechanism remains intact (Brown et al. 2025; Gross et al. 2024). Systems exhibiting negative priming alongside stable biochar stocks offer greater C sequestration potential (Fig. 8a and b), and models assessing biochar-based CO_2 removal should account for these additional benefits. Conversely, systems showing pronounced positive priming of soil organic matter or elevated biochar dissipation (Fig. 8c and d) require further research attention. If biochar is to be used effectively for CO_2 removal, it should be applied to soils where the highest sequestration effect is expected. Furthermore, measures should be implemented to retain biochar particles within the plant root zone, thereby supporting water and nutrient availability necessary for plant growth.

Physical weathering of biochar after field exposure is likely to alter the stability and long-term persistence of C derived from biochar. For example, Naisse et al. (2015) noticed that physical weathering of biochars induced by successive wetting/drying and freezing/thawing cycles resulted in 10–40% of total C loss depending on the feedstock, which is related to leaching dissolved and particulate C compounds. However, physical weathering increased the biological stability of biochar, thereby affecting their priming effects on soil native C. Williams et al. (2019) noticed that although continued solubilization of increasingly aromatic biochar-C compounds occurred during short-term weathering of biochar under field conditions, this accounted for a relatively small proportion of biochar C and there was little to no change in biochar stability or C sequestration potential.

5.3 Soil remediation

Biochar has received considerable attention as an amendment for remediating contaminated soils. Applied biochar can immobilize soil contaminants via several mechanisms including electrostatic interactions, surface complexation, precipitation, and physical entrapment (Li et al. 2017; Luo et al. 2022). Moreover, biochar applications typically increase the pH of soil, increasing the affinity of variable-charge soil minerals for cationic contaminants while also reducing the solubility of metal-bearing solid phases (Xu et al. 2016). Following application to soil, biochar is subjected to various weathering reactions that change its physical and chemical properties (as discussed above). These changes in biochar properties can affect pollutant mobility over time due to changes in the contaminant speciation at the biochar surface and within the surrounding soil/water environment (Rechberger et al. 2019; Wei et al. 2023). To ensure the long-term viability of biochar-based soil remediation efforts, it is crucial to understand the effect of weathering on biochar's affinity for soil contaminants.

5.3.1 Heavy metals

Heavy metal contamination of soils is a widespread environmental problem (Nagajyoti et al. 2010; Tóth et al. 2016). Biochar is an attractive amendment for remediating metal-contaminated soils due to its high affinity for wide range of heavy metal pollutants (Ji et al. 2022; Nguyen et al. 2023). Several researchers employed artificial weathering techniques such as chemical oxidation, freeze–thaw cycling, wet-dry cycling, and natural weathering (applying biochar to soil and then recovering the biochar) to obtain weathered biochars and assess their performance as metal sorbents (Liu and Chen 2022). In general, these researchers found that weathering alters the affinity of biochar for metal contaminants via changes in surface functionality, alkalinity and composition of the ash content, and physical transformations.

Within soil, the oxidation of the biochar surface can yield oxygen-containing functional groups, mainly carbonyl (–C=O), carboxyl (–COOH), and phenolic (–H) groups, which tend to increase a biochar's affinity for metal cations (Zhong et al. 2020). The formation of these groups aids in the sorption of heavy metal cations via two main mechanisms: first, the deprotonation of the proton-active groups (–COOH, pKa ~4; –OH, pKa ~10) along with the polar nature of the carbonyl group increases the negative surface charge of the biochar, increasing the electrostatic attraction of cations in the soil solution (Fan et al. 2018; Xiao et al. 2020); second, sorption via metal cation coordination with deprotonated carboxyl and phenolic groups increases with the abundance of oxygen-containing surface groups (Alam et al. 2018; Wang et al. 2020b). Hao et al. (2017) reported a nearly three-fold increase in the Cu sorption capacity of cotton biochar after wet/dry weathering, correlated with an increase in

the biochar's oxygen-containing functional groups. Similarly, an increase in the abundance of oxygen-containing functional groups was credited for 45–72% increases in the Cu and Zn sorption capacity of corn straw biochar after freeze–thaw weathering (Wang et al. 2021b). Others reported similar results (Fan et al. 2018; Zhong et al. 2020; Yuan et al. 2021). However, an increase in the oxygen-containing functional groups of biochar after weathering does not always result in an increase in biochar's sorption of metal cations. The sorption capacity of Cu by peanut biochar decreased by half after wet-dry weathering while the Cd sorption capacities of green waste or rice straw biochars showed similar decreases after weathering (Hao et al. 2017; Ke et al. 2023; Meng et al. 2024). The difference in the effect of biochar weathering on the adsorption of heavy metals depends on the heavy metal type, nature of biochar feed stock material, and the distribution of dissolved organic compounds and functional groups in biochar (Yuan et al. 2021). While weathering enhances Cu adsorption by biochar through increases in surface area, it can result in a decrease in Cd adsorption/complexation through a decrease in dissolved organic compound.

Weathering affects electrostatic interactions between the biochar surface and metal oxyanions via two competing processes. The addition of oxygen-containing functional groups increases the negative surface charge and reduces the electrostatic attraction of metal oxyanions (Wang et al. 2017). In contrast, weathering tends to reduce the pH of biochar towards its pH of net zero charge (typically < 3; Mukherjee et al. 2011), increasing the electrostatic attraction of metal oxyanions (Lawrinenko and Laird 2015). Lawrinenko et al. (2016) determined the anion exchange capacity (AEC) of three biochars after artificial weathering using alkaline H_2O_2. They found that the AEC of weathered biochars was reduced by up to 54%, attributed to the reduction of oxonium to ether. These results are consistent with an earlier study by Cheng et al. (2008), where 100% reductions in AEC of biochar incubated for 12 months at 70 °C were reported compared to fresh biochar. Such reductions in AEC can reduce the sorption of oxyanions by weathered biochar as reported for chromate [Cr(VI)] and arsenate [As(VI)] (Nagodavithane et al. 2014; Wang et al. 2017; Jiang et al. 2024). Despite reductions in electrostatic attraction upon weathering, metal oxyanions can form complexes with carboxyl and phenolic groups via ligand exchange with surface coordinated hydroxyls (Zhang et al. 2015a, b; Oh et al. 2021), possibly increasing their retention by weathered biochars. To this end, Liu et al. (2024) demonstrated that arsenite [As(III)] release was less from weathered biochars than fresh biochars, attributed to a higher abundance of oxygen-containing functional groups on the biochar surface. Likewise, the increased sorption of As(III) by weathered sewage sludge-derived biochar compared to fresh biochar was ascribed to enhanced ligand exchange with oxygen-containing surface groups (Wang et al. 2017).

The coprecipitation of heavy metals with components of the biochar ash content is a major mechanism of metal immobilization in soils (Li et al. 2017). Weathering reduces the reactivity of the biochar ash content due to mineral dissolution and leaching of metal precipitate-forming anions like CO_3^{2-} and PO_4^{3-} (Xu et al. 2018). Furthermore, the dissolution of carbonates, leaching of base cations, and addition of acidic surface functional groups reduce the pH of biochar, resulting in conditions less favorable for heavy metal precipitation (Liu and Chen 2022; Long et al. 2024). For example, Cd carbonate precipitation was a dominant mechanism of Cd immobilization by fresh rice straw-derived biochar; however, no evidence of Cd carbonate precipitation was found for weathered biochar (Meng et al. 2023). Xie et al. (2022) also reported Pb sorption by fresh corn straw biochar via the formation of metal hydroxide and carbonate precipitates whereas metal precipitation was not observed for Pb sorption by weathered biochar. Likewise, Rechberger et al. (2019) reported reduced contributions of $Cu(OH)_2$ and $CuCO_3$ phases towards Cu immobilization in wood chip biochar-amended soils after 15 months of weathering. Similar findings were reported in several other cases (Xu et al. 2018; Meng et al. 2022a; Ke et al. 2023; Hu et al. 2024). Overall, these results suggest that the immobilization of heavy metals via coprecipitation with biochar ash components is diminished by weathering and should be accounted for when considering the long-term viability of biochar-based soil remediation.

While several studies have investigated the sorption of heavy metals by weathered biochars from aqueous solution, fewer studies have assessed the effect of biochar weathering on the immobilization of metals in soil. Investigations of the effects of biochar weathering on the remediation of metal-contaminated soils prior to 2021 were summarized by Wang et al. (2021a). Table 3 summarizes the findings of more recent studies. In several cases, the immobilization of heavy metals in soils was improved after biochar weathering. For instance, wheat straw biochar significantly reduced phytoavailable Cd and Ni from contaminated soil after biochar/soil mixtures were weathered using wet-dry cycling (Yang et al. 2021). Similarly, Chen et al. (2021b) reported significant increases in the stable Pb fraction over time in soils amended with corn straw biochar and weathered using freeze–thaw cycling. A positive effect of weathering on metal immobilization was reported by several others (Table 3). However, reduced metal immobilization due to

Table 3 Summary of selected field-based and lab-based studies focused on the effect of biochar weathering on the immobilization of contaminants in soil

Biochar feedstock	Pyrolysis temperature (°C)	Contaminants of interest	Type of experiment	Duration/aging method	Overall result	Reference
Mixed conifer	1400	Al^{3+}, Cu^{2+}, Zn^{2+}	Field-based	23 months	–	Johnson et al. (2024)
Olive pit, rice husk	500	As^{3+}, Ba^{2+}, Cu^{2+}, Pb^{2+}, Zn^{2+}	Field-based	2 years	–	Campos et al. (2021)
Rice husk	500	Cd^{2+}	Field-based	1 year	+	Hou et al. (2022)
Litchi wood	600	Cd^{2+}, Cu^{2+}, Pb^{2+}	Field-based	3 years	+	Chen et al. (2024)
Rice husk, soft wood, oilseed rape straw, miscanthus straw, sewage sludge, wheat straw	550, 700	As^{3+}, Cd^{2+}, Cu^{2+}, Mn^{2+}, Ni^{2+}, Pb^{2+}, Sb^{3+}, Zn^{2+}	Lab-based	Wet/dry, freeze/thaw, H_2O_2, natural aging (7 months)	+/–	Yang et al. (2022b)
Softwood	700	As^{3+}, Sb^{3+}	Lab-based	Acidic leaching	–	Wang et al. (2022b)
Poultry litter, sugar gum wood	550	Cd^{2+}	Lab-based	60% WHC for 270 days	+	Bandara et al. (2021)
Mucai mushroom spent substrate	600	Cd^{2+}	Lab-based	Freeze/thaw, acid wash, microbial aging	+/–	Qu et al. (2022)
Pennisetum sinese straw	400	Cd^{2+}, Cu^{2+}	Lab-based	Wet/dry, freeze/thaw	+	Cui et al. (2021)
Rice straw	400	Cd^{2+}, Cu^{2+}, Ni^{2+}	Lab-based	Wet/dry, freeze/thaw	+	Meng et al. (2022c)
Wheat straw, corn straw	500	Cd^{2+}, Ni^{2+}	Lab-based	Wet/dry, freeze/thaw	+	Yang et al. (2021)
Chicken manure, wheat straw	500	Cd^{2+}, Pb^{2+}	Lab-based	Wet/dry, freeze/thaw	+/–	Yang et al. (2023)
Wheat straw, corn straw, peanut shell, pine chips	450	Pb^{2+}	Lab-based	Freeze/thaw, high temperature, 40% WHC	+	Chen et al. (2021b)
Oak	550	Imazamox, Terbuthylazine, Picloram	Lab-based	Incubation at 30% WHC	+	Gámiz et al. (2019)
Corn stalk	400, 600	Lindane	Lab-based	Wet/dry	–	He et al. (2021)
Hardwood	750	PFAS	Lab-based	Dry age for 4 years	–	Navarro et al. (2023)
Mixed wood	450	Simazine	Lab-based	Field-aged	+	Cheng et al. (2024)

biochar weathering has also been observed. Wang et al. (2022b) simulated 100 years of rainfall-induced weathering on Mg/Fe modified soft wood biochar-amended soil by repeatedly applying an acidic solution to biochar/soil mixtures and monitored As and Sb in the leachate over time. After ~ 40 years of simulated weathering, biochar's ability to immobilize both species was diminished, although the mobility of Sb was more affected by weathering than As. Likewise, the leaching of a range of heavy metals increased over time from soil amended with different types of biochar and weathered using various methods (Yang et al. 2022a).

Most studies on metal immobilization in soils have used artificial weathering to simulate long-term effects of biochar weathering. In this regard, field-based studies may give a better representation of long-term remediation efforts under natural conditions. Johnson et al. (2024) performed a field experiment focused on the remediation of pyritic mine tailings by applying a mixture of biochar, biosolids, and lime. Immediately after application, $CaCl_2$-extractable metals were below quantifiable levels. However, after 2 years, $CaCl_2$-extractable Al, Cu, and Zn were substantially increased. This may be due to the decrease in soil pH from 7.7 immediately after application to 4.8 two years later. In contrast, Cheng et al. (2024) found that Litchi wood biochar application to an acidic soil decreased the mobility of Cd, Cu, and Pb even after three years. After application, biochar increased the soil pH by ~ 1.5 pH units. The soil pH decreased after 1 year; however, pH decreases levelled off, and increases in the oxygen-containing functional groups of biochar were able to maintain metal immobilization (Chen et al. 2024). Because additional external factors such as plant/microbial exudates and changes in soil structure can affect long-term metal immobilization (Wang et al. 2021a; Long et al. 2024), additional field experiments are needed to further understand the effect of biochar weathering on soil remediation under natural conditions.

Overall, the results of the above studies are mixed, with biochar weathering either increasing, decreasing,

or having no effect on heavy metal mobility in soils. This is mainly due to differences in soil properties, biochar properties, and the method of the weathering process. For soils, the dominant property controlling the overall effect of biochar weathering on metal mobility is soil pH (Yuan et al. 2021; Yang et al. 2022a). The two main contributions of biochar additions to heavy metal contaminated soils are reactive sites and alkalinity. As such, in alkaline soils where biochar additions have little effect on pH, weathering tends to increase the reactivity of biochar and long-term metal immobilization is favored (Chen et al. 2021b; Yang et al. 2021). For acidic soils, however, the biochar-induced pH increase is transient; as biochar weathering proceeds, the pH of the soil trends back to its original acidic value (Rechberger et al. 2019; Wang et al. 2021a). In this case, there is a temporary decrease in metal mobility followed by remobilization at longer time scales (Johnson et al. 2024). Differences in biochar properties greatly influence its response to weathering; under identical experimental conditions, different biochars can either promote metal immobilization or have little effect (Yang et al. 2021). Generally, manure-derived biochars produced at high temperature are more resistant to weathering in terms of metal immobilization than plant-derived or lower temperature biochars (Yuan et al. 2021). However, because the effect of biochar properties is so variable, further work on the relationship between biochar properties and long-term soil remediation is necessary. During lab-based studies, the method of artificial weathering has a large influence on metal immobilization (Liu and Chen 2022). For example, Meng et al. (2022a) subjected biochar/soil mixtures to five different artificial weathering procedures and sequentially extracted Cd to determine its partitioning in the stable soil fraction. Weathering by leaching significantly increased the stable Cd fraction; however, the other four weathering methods reduced the stable Cd fraction. Therefore, while artificial weathering experiments can provide valuable information on the effects of biochar weathering, caution should be used when extending lab-based results to field-scale applications.

5.3.2 Organic pollutants

Organic contaminants are introduced to soil via several pathways including pesticide application, soil amendment using animal manures or biosolids, and irrigation with reclaimed wastewater (Valentín et al. 2013). Biochar's high affinity for various organic compounds makes it an ideal amendment for reducing the mobility and bioavailability of organic pollutants in soil (Luo et al. 2022). However, weathering can alter biochar's performance as an adsorbent for organic contaminants. For example, after natural weathering in soil near roots for 90 days, pig manure biochar produced at 700 °C had lower affinity for both atrazine and phenanthrene than fresh biochar (Ren et al. 2016). Similarly, the sorption of atrazine by corn stalk biochar decreased after oxidative weathering (Liu et al. 2019a, b). Navarro et al. (2023) evaluated the leaching of a range of per- and poly-fluoroalkyl substances (PFAS) from hardwood biochar-amended soils after a 4-year incubation period. Compared to unweathered biochar/soil mixtures, PFAS leaching after 4 years was substantially greater. The C chain on PFAS facilitates binding to biochar via hydrophobic interactions. The hydrophobicity of biochar decreases with weathering (Rechberger et al. 2019), which may explain weaker PFAS retention in weathered biochar/soil mixtures.

Biochar weathering has also been shown to increase the sorption of organic contaminants. Oak wood biochar that had been weathered in soil for 6 months showed up to an 80-fold increase in its sorption of picloram, imazamox, and terbuthylazine compared to unweathered biochar (Gámiz et al. 2019). Walnut shell biochar that had been weathered in soil for 6 months had a ~15% higher sorption capacity for metolachlor than fresh biochars (Liu et al. 2021). Cheng et al. (2024) applied fresh and weathered mixed wood biochar to soils and monitored simazine mineralization and leaching potential. Compared to unamended soil, both fresh and weathered biochar reduced the leaching potential of simazine; however, simazine mineralization was significantly higher in the weathered than in the fresh biochar treatment. Higher simazine mineralization in soils amended with weathered biochar may be due to a reduction in the content of microbially toxic substances in biochar after ageing (He et al. 2021), suggesting that weathering may have little effect on the affinity of biochar for some organic pollutants while also reducing the suppression of the activity of certain soil microbes to degrade the contaminant. However, this effect is likely biochar-, soil-, and organic pollutant-dependent, and should be further explored to ensure the viability of the biochar-based remediation of soils containing organic contaminants.

5.3.3 Contaminant remobilization from biochar weathering

The efficacy of soil remediation using biochar depends on its long-term ability to retain contaminants. Changes in the biochar's pH, surface functionality, and physical structure may induce the release of initially immobilized contaminants and should be considered in risk assessments of biochar-based remediation strategies.

Weathering reduces biochar pH via dissolution of the ash content, leaching of base cations, and formation of acidic surface functional groups (Zhao et al. 2015; Chen et al. 2021c). Such reductions in biochar pH can remobilize soil contaminants, especially metal cations, through

the dissolution of metal-bearing surface precipitates and weakening electrostatic binding. For example, Cui et al. (2024) found that subjecting corn straw-derived biochar/soil mixtures (2% by weight) to chemical oxidation, freeze/thaw, and wet/dry cycles decreased biochar pH from about 10 to 5, corresponding with shifts of residual Cd, Cu, and Pb to the more mobile exchangeable fraction. Likewise, Meng et al. (2022b) observed that rice straw-derived biochar added to an acidic soil (3% by weight) initially increased soil pH, but after simulating 5 years of weathering, reductions in pH increased available Cd. Increased contaminant mobility in biochar-amended soil due to pH declines upon weathering was also shown by others (Shen et al. 2018; Campos et al. 2021; Johnson et al. 2024). Because biochar-induced increases in soil pH are transient (Pignatello et al. 2015; Apostolović et al. 2024), pH decline after biochar amendment should be anticipated in remediation planning.

Biochar hydrophobicity decreases during weathering due to the formation of oxygen-containing surface functional groups (Ivanova et al. 2023). Lower hydrophobicity reduces biochar's affinity for a range of organic contaminants (Ren et al. 2018; Liu et al. 2025), potentially promoting their remobilization in soil. Such effects may account for the greater desorption of atrazine and diuron from paper mill sludge biochar-amended soil after 32 months and increased PFAS leaching from hardwood biochar-amended soil after 4 years (Martin et al. 2012; Navarro et al. 2023). Although weathering typically increases biochar's abundance of oxygen-containing functional groups, the opposite has been demonstrated. Freeze/thaw weathering reduced the abundance of active carboxyl groups in pinecone-derived biochar (Shen et al. 2024), while wheat straw-derived biochar incubated for 2 years in alkaline soil had a lower abundance of hydroxyl groups (Rechberger et al. 2017). Both groups are important for the sorption of metal cations (Alam et al. 2018; Wang et al. 2020a, b), and their elimination via biochar weathering may induce desorption of contaminants back into the soil solution (Cui et al. 2024).

The physical weathering of biochar can degrade its structure and result in the release of contaminants in biochar-amended soil. Biochar fragmentation can produce mobile colloids which act as carriers for bound contaminants, facilitating their remobilization in soil as physical weathering progresses. Ma et al. (2023) demonstrated that biochar colloids enhanced the mobility of various organic contaminants in a sandy soil, while similar results were shown for Cr, U, and other pollutants (Chen et al. 2022b; Sun et al. 2022; Sharma et al. 2025). Furthermore, physical weathering can promote the collapse of biochar macropores to micropores (Goñi-Urtiaga et al. 2022; Cui et al. 2024). Because the long-term sequestration of pollutants by biochar is aided by contaminant intraparticle diffusion through macropores (Liu et al. 2019a, b), loss of biochar microporosity limits further internal diffusion and possibly promotes contaminant diffusion back into the soil solution. Moreover, the collapse of the biochar pore structure may expose internally sequestered pollutants to the soil solution where desorption is more favorable (Han et al. 2018). However, disentangling the mechanisms of contaminant release due to biochar physical weathering requires further investigation.

6 Conclusions and future research needs

The review has indicated that although biochar contains stable C, when exposed in the field, biochar is subjected to physical, chemical and biological weathering processes (i.e., aging), thereby leading to physical fragmentation and chemical transformation. The main findings of this review are summarized below:

- Weathering-initiated changes in biochar have been shown to affect the nature, characteristics and reactivity of biochar, and significantly alter the interactions between biochar and soil components including microorganisms, thereby impacting C sequestration and soil remediation potentials of biochar.
- Weathering-induced disintegration of biochar particles increases particle mobility through the soil pore systems, i.e., moved by infiltration and especially in the form of colloidal transport process.
- When evaluating the C sequestration potential of biochar-amended soils, it is essential to consider not only changes in biochar stocks but also in native soil organic matter stocks, alongside weathering and dissipation processes. Biochar dissipation in soil as influenced by weathering process is likely to impact C sequestration potential.
- Reductions in biochar pH can remobilize soil contaminants, especially metal cations, through the dissolution of metal-bearing surface precipitates and weakening electrostatic binding.
- Biochar weathering significantly impacts both its economic viability and life cycle assessment (LCA) by altering its properties, which affect its long-term stability, agronomic benefits, and potential for C credits (Li et al. 2024; Matuštík et al. 2020).
- Weathering primarily affects economic viability by influencing the longevity and effectiveness of biochar benefits, which determines whether its application is profitable for farmers. The impact of biochar weathering on LCA needs to account for the dynamic changes during weathering to provide an accurate environmental impact assessment and promote LCA

perspectives in relation to C sequestration and co-benefits.

Due to the limited state of knowledge on the impact of weathering on the potential value of biochar in C sequestration, soil health, and remediation of contaminated sites, the following research needs exist:

- Elucidation of the mechanisms involved in the biogeochemical process of weathering of biochar under field conditions
- Understanding the soil and environmental factors affecting the long-term stability and weathering of biochar
- Examining the weathering-induced physical fragmentation and biochemical transformation of biochar using advanced analytical techniques, particularly targeting changes in the electronic hybridization of the carbon atoms within biochar (e.g., sp^1, sp^2, and $sp.^3$ hybridization states)
- Quantification of the impacts of weathering of biochar on the potential values of biochar in C sequestration, soil health, and remediation of contaminated sites
- Development of a concrete proposal for a standardized observation protocol and detailed database for biochar weathering across regions and scales

Supplementary Information

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Supplementary material 1.

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