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Biochar as a climate-smart tool for long-term soil carbon sequestration: A comprehensive review

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Abstract

Anthropogenic climate change, driven by escalating atmospheric greenhouse gas (GHG) concentrations, necessitates scalable negative emission technologies alongside deep emissions reductions. Agriculture occupies a pivotal position in global carbon dynamics, serving both as a major emitter and as a vital sink potential. Biochar, which is a carbon-rich, highly porous, pyrogenic material produced via the thermochemical pyrolysis of biomass under oxygen-limited conditions, has emerged as a frontline climate-smart tool for persistent soil carbon sequestration. This paper comprehensively reviews the synthesis, physicochemical transformations, recalcitrance mechanisms, agronomic impacts and carbon abatement efficacy of biochar amendments. Pyrolysis temperature (300°C to 700°C) and feedstock composition fundamentally govern biochar properties, dictating aromaticity, cation exchange capacity (CEC) and specific surface area. Biochar stabilizes soil organic carbon (SOC) through three main pathways: biological recalcitrance derived from condensed polycyclic aromatic ring structures, physical encapsulation within soil micro- and macro-aggregates and organo-mineral complexation with clay minerals and iron or aluminum oxides. Long-term carbon residence time models indicate half-lives ranging from centuries to millennia when atomic H/C_{org} ratios remain below 0.4. Simultaneously, biochar application yields substantial agronomic co-benefits, including enhanced water holding capacity, reduced nutrient leaching, improved CEC and mitigation of soil nitrous oxide (N₂O) and methane (CH₄) emissions. However, widespread deployment faces constraints related to feedstock supply chain logistics, potential heavy metal or polycyclic aromatic hydrocarbon (PAH) contamination, site-specific soil dynamics and economic viability. This review provides a synthesis of mechanistic pathways, highlights critical research gaps and outlines policy and carbon market integration protocols necessary to realize the full potential of biochar in climate-smart agriculture.

Keywords: Biochar, climate-smart agriculture, soil carbon sequestration, pyrolysis, recalcitrance, GHG abatement, Organo-mineral interaction.

Introduction

Global atmospheric carbon dioxide (CO₂) concentrations have surpassed 420 ppm, representing a steep increase from pre-industrial levels of ~280 ppm and driving accelerating planetary warming, altered precipitation regimes and heightened extreme weather frequency [24, 38]. The Intergovernmental Panel on Climate Change (IPCC) sixth assessment report underscores that reaching net-zero greenhouse gas (GHG) emissions requires not only aggressive decarbonization across energy and industrial sectors but also the rapid scaling of land-based Negative Emission Technologies (NETs) [58]. Agricultural ecosystems manage over 38% of global ice-free land surface, making soil management a cornerstone of climate mitigation strategies [17].

Soil organic carbon (SOC) represents the largest terrestrial carbon pool, holding approximately 1,500 to 2,400 Pg of organic carbon in the top meter, representing more than double the atmospheric carbon reservoir and triple the carbon contained in living vegetation [29, 53]. However, centuries of intensive tillage, deforestation, residue removal and unsustainable agricultural practices have degraded global agricultural soils, releasing an estimated 116 Pg of carbon into the atmosphere [52]. Restoring depleted SOC stocks is therefore essential both for global climate regulation and for sustaining soil security, crop productivity and food supply chains. Conventional soil carbon sequestration techniques,

such as cover cropping, reduced or zero tillage and organic manure incorporation, enhance carbon inputs to the soil. However, labile organic carbon added via crop residues or compost exhibits relatively short residence times, with 70% to 90% mineralizing back into CO₂ within 1 to 5 years under microbial decomposition [26, 54]. Furthermore, biomass carbon sequestered through conventional practices remains vulnerable to reversal upon management changes, drought, or soil disturbance.

In contrast, biochar, defined as a carbon-dense solid byproduct derived from the thermochemical conversion of biomass in oxygen-limited environments via pyrolysis, offers a persistent carbon capture mechanism [40, 60]. By transforming readily decomposable plant materials into chemically condensed aromatic structures, biochar locks atmospheric carbon fixed by photosynthesis into an extraordinarily stable pool that resists microbial and chemical degradation for centuries to millennia [62]. Inspired by the ancient Amazonian Terra Preta de Índio (Dark Earths), which maintain elevated SOC and fertility thousands of years after formation, modern agricultural research positions biochar as a dual-action, climate-smart technology: sequestering carbon while simultaneously improving soil physical, chemical and biological properties [19, 61].

This review provides a comprehensive synthesis of biochar as a long-term soil carbon sequestration tool within climate-smart agriculture. Specifically, we examine: (i) feedstock selection and pyrolysis dynamics; (ii) physical, chemical and organo-mineral stabilization mechanisms; (iii) agronomic impacts on CEC, water dynamics and crop yields; (iv) non- CO₂ GHG mitigation potential; and (v) operational barriers, ecotoxicological safety and carbon market frameworks.

2. Feedstock dynamics, pyrolysis parameters and biochar characterization

Biochar production involves the thermal decomposition of organic feedstock at elevated temperatures (typically 300°C to 700°C) in the complete or partial absence of oxygen [1]. The resulting biochar properties depend fundamentally on two primary factors: the intrinsic composition of the feedstock biomass and the operational parameters of the pyrolysis process [64].

Table 1: Physicochemical properties of biochar synthesized across diverse feedstocks and pyrolysis temperatures [Adapted from] [21, 24, 26].

Feedstock Type	Pyrolysis Temp (°C)	Biochar Yield (%)	Fixed C (%)	Atomic H/Corg	BET Surface Area (m ² /g)
Softwood Sawdust	350 (Slow)	38.5 %	62.4 %	0.68	12.4 m ² /g
Softwood Sawdust	700 (Slow)	24.2 %	88.7 %	0.18	345.0 m ² /g
Wheat Straw	400 (Slow)	32.1 %	54.8 %	0.52	28.5 m ² /g
Poultry Litter	500 (Slow)	41.0 %	38.2 %	0.41	45.2 m ² /g

3. Mechanisms of long-term soil carbon sequestration

The persistence of biochar carbon in soil ecosystems is governed by a multi-tier stabilization framework comprising chemical recalcitrance, physical encapsulation within soil aggregates and organo-mineral interactions [44].

3.1 Chemical recalcitrance and molecular structure

The primary mechanism underpinning biochar stability is chemical recalcitrance derived from thermal condensation. During pyrolysis, unstable aliphatic structures undergo cyclization and condensation, forming extensive graphenic networks of fused polycyclic aromatic rings linked by C-C bonds [55]. These aromatic ring systems possess high resonance energy and lack accessible enzymatic cleavage sites, rendering them extremely resistant to microbial attack and chemical

2.1 Feedstock selection and composition

A wide range of organic materials can serve as biochar feedstocks, including crop residues (e.g., wheat straw, corn stover, rice husk), forestry residues (e.g., pine wood, hardwood sawdust), animal manures (e.g., poultry litter, dairy manure) and municipal bio-solids [25, 73]. Lignocellulosic feedstocks high in lignin, such as woody biomass, yield biochars characterized by higher fixed carbon recovery, denser aromatic structures and greater thermal stability. Conversely, feedstocks rich in cellulose, hemicellulose and inorganic ash (such as grasses and manure) yield biochars with higher cation exchange capacity, elevated pH and higher ash content, but lower fixed carbon yield [14, 47].

2.2 Pyrolysis technologies and temperature regimes

Pyrolysis regimes are broadly classified into slow pyrolysis, fast pyrolysis and gasification [5]. Slow pyrolysis, characterized by long vapor residence times (minutes to hours) and moderate heating rates (5°C to 30°C/min), is the optimal pathway to maximize solid biochar yield (typically 25% to 40% of dry biomass mass). Fast pyrolysis prioritizes bio-oil yield, resulting in biochar yields of 10% to 20%, while gasification produces biochar yields below 10% as a low-density mineral residue [11].

Pyrolysis temperature exerts a dominant influence on biochar chemistry. As temperature increases from 300°C to 700°C, volatile organic compounds are progressively driven off, accompanied by the dehydration and decarboxylation of aliphatic biopolymers [33].

This process induces extensive aromatization, transforming random aliphatic chains into fused polycyclic aromatic hydrocarbon sheet structures [46]. Consequently, high-temperature biochars (>500°C) exhibit elevated elemental carbon content (>70%), lower atomic Hydrogen-to-Carbon (H/C) and Oxygen-to-Carbon (O/C) ratios, larger specific surface area (up to 400 m²/g) and higher porosity. In contrast, low-temperature biochars (<400°C) retain residual oxygenated functional groups (e.g., carboxyl, hydroxyl, phenolic), providing higher initial CEC but lower physical recalcitrance [65, 75]. Table 1 summarizes the impact of feedstock type and pyrolysis temperature on key biochar physicochemical characteristics.

oxidation [2].

The European Biochar Certificate (EBC) and International Biochar Initiative (IBI) specify the atomic H/Corg molar ratio as the primary standard for assessing biochar stability [12]. Biochars with an H/Corg ratio < 0.4 possess high aromatic condensation, corresponding to predicted soil residence times exceeding 1,000 years under temperate and tropical soil environments [7]. Biochars with H/Corg ratios between 0.4 and 0.7 demonstrate intermediate stability (100 to 1,000 years), whereas materials with H/Corg > 0.7 retain significant aliphatic fractions and decompose rapidly [35].

3.2 Aggregate formation and physical encapsulation

In addition to chemical recalcitrance, biochar promotes soil

structural stability through aggregate formation [6]. When incorporated into soil, biochar particles interact with native organic matter, fungal hyphae and root exudates to form stable micro-aggregates (<250 µm) and macro-aggregates (>250 µm) [49]. Physical encapsulation within aggregates physically isolates biochar particles and associated native SOC from soil decomposers and extracellular enzymes, restricting oxygen diffusions and slowing decomposition rates [57].

3.3 Organo-mineral interactions and surface aging

As biochar ages in the soil environment, abiotic and biotic weathering oxidation processes generate oxygen-containing functional groups (carboxyl -COOH, hydroxyl -OH, carbonyl -C=O) on particle surfaces [30]. These functionalized surfaces engage in ligand exchange, hydrogen bonding and cation bridging with soil clay minerals, amorphous iron (Fe) oxides and aluminum (Al) hydroxides [69]. These organo-mineral complexes physically shield biochar and co-located labile SOC, creating

highly stable mineral-associated organic matter (MAOM) complexes [34].

3.4 Soil organic carbon priming dynamics

Biochar addition influences the mineralization rate of native soil organic carbon, a phenomenon known as the 'priming effect' [36]. Short-term positive priming (accelerated native SOC decomposition) may occur immediately following biochar application, driven by the input of trace labile volatile organic compounds present on biochar surfaces, which stimulate microbial biomass activity [71]. However, long-term studies overwhelmingly report a transition to negative priming (suppressed native SOC decomposition) [70]. Negative priming occurs due to: (i) adsorption of labile native organic compounds onto biochar's porous inner surfaces; (ii) inactivation of extracellular enzymes via surface sorption; and (iii) enhanced aggregate stability protecting native SOC [13, 15].

Table 2: Summary of biochar stabilization pathways, governing drivers and carbon persistence horizons [4, 15, 70].

Stabilization Pathway	Primary Mechanism	Key Biochar / Soil Drivers	Estimated Carbon Residence Time
Chemical Recalcitrance	Fused polycyclic aromatic C-C ring condensation	Pyrolysis temp > 500°C; H/Corg ratio < 0.4	Centuries to Millennia (500 to 2000+ years)
Physical Encapsulation	Occlusion within micro- and macro-aggregates	Soil texture, fungal hyphae, root exudates	Decades to Centuries (50 to 300 years)
Organo-Mineral Complexation	Sorptive binding with Fe/Al oxides & phyllosilicates	Clay content, cation bridging, surface carboxyls	Centuries (100 to 800 years)
Negative Priming	Sorption of native SOC & extracellular enzyme immobilization	High surface area biochar; microbial community shift	Sustained long-term stabilization

4. Impact on soil health and agronomic productivity

Beyond carbon sequestration, biochar acts as a powerful soil conditioner, delivering multifaceted agronomic co-benefits that improve soil physical structure, chemical fertility and biological activity [27].

4.1 Hydrological dynamics and water holding capacity

Biochar's highly porous internal structure significantly alters soil physical hydraulics [4]. In coarse-textured sandy soils, biochar amendments increase plant-available water capacity (AWC) by introducing intra-particle nanopores and micropores, reducing gravity-driven percolation losses [32]. Global meta-analyses reveal that biochar additions at rates of 10 to 30 t/ha enhance soil water holding capacity by an average of 15% to 25% in coarse soils [50]. In fine-textured clay soils, biochar improves soil aeration, lowers bulk density and enhances water infiltration rates by creating inter-particle macropores, thereby mitigating waterlogging and runoff erosion [48].

4.2 Cation exchange capacity and nutrient retention

Fresh biochar exhibits low CEC, but as it oxidizes in soil, carboxylate (-COO-) and phenolate (-O-) surface functional groups develop, dramatically expanding the soil's CEC [42]. This expanded CEC enables biochar to retain essential nutrient cations, such as ammonium (NH₄⁺), calcium (Ca²⁺), magnesium (Mg²⁺) and potassium (K⁺), thereby preventing vertical leaching into groundwater during rainfall events [37]. Furthermore, biochar can reduce nitrate (NO₃⁻) leaching by up to 40% through direct electrostatic interaction, water retention and microbial immobilization [10].

4.3 Soil microbial ecology and enzymatic activity

Biochar pores serve as protective micro-habitats for soil bacteria, actinobacteria and mycorrhizal fungi, sheltering them

from soil predators (e.g., protozoa and nematodes) and desiccation stress [68]. Biochar amendments stimulate arbuscular mycorrhizal fungal (AMF) colonization by altering signaling pathways and nutrient availability [51]. Concurrently, biochar application shifts microbial community structure, increasing the ratio of bacterial-to-fungal biomass and promoting microbial enzyme production involved in carbon, nitrogen and phosphorus cycling [41].

4.4 Agroecosystem yield responses

Agronomic crop response to biochar application varies depending on soil type, crop species and climate zone [3]. Meta-analyses show that yield responses are most pronounced in highly weathered, acidic tropical soils (e.g., Ferralsols, Acrisols), where average yield increases of 20% to 40% are observed due to soil acidity neutralization (liming effect), CEC enhancement and phosphorus availability [43]. In temperate, fertile soils (e.g., Chernozems, Luvisols), crop yield responses are typically modest (0% to 10%), with primary benefits manifesting as drought resilience and nutrient use efficiency gains [74].

5. Climate change mitigation potential and greenhouse gas abatement

Biochar contributes to climate change mitigation through both direct carbon sequestration and the abatement of non- CO₂ soil GHG emissions [31].

5.1 Global mitigation scale and carbon accounting

Global modeling by Woolf *et al.* [72] demonstrates that biochar implementation could sequester up to 1.8 Pg CO₂-equivalent (CO₂e) per year, representing approximately 12% of current anthropogenic GHG emissions, without compromising food

security or land availability. Over a 100-year horizon, the cumulative net mitigation potential exceeds 130 Pg CO₂e^[59]. The net carbon balance of biochar depends on life-cycle assessment (LCA) accounting, which incorporates biomass collection, transport, pyrolysis energy recovery, biochar soil spreading and avoided baseline emissions^[45].

5.2 Mitigation of nitrous oxide (N₂O) and methane (CH₄) emissions

Nitrous oxide (N₂O) is a potent GHG with a global warming potential 273 times greater than CO₂ over a 100-year timescale. Field and laboratory studies demonstrate that biochar soil amendment suppresses agricultural soil N₂O emissions by an average of 30% to 70%^[9]. The mechanisms underlying N₂O reduction include: (i) increased soil aeration, which suppresses anaerobic denitrification pathways; (ii) biochar acting as an electron shuttle, facilitating the complete reduction of N₂O to inert N₂ gas via enhanced nitrous oxide reductase (nosZ) gene expression; and (iii) sorption of ammonium and nitrate ions, reducing substrate availability for nitrifying and denitrifying microbes^[21, 63].

For methane (CH₄), biochar application to flooded paddy rice fields can decrease CH₄ flux by 15% to 45% by promoting methanotrophic bacterial activity in the rhizosphere through enhanced aeration and electron transport networks^[16].

6. Constraints, ecotoxicological risks and future directions

Despite its compelling potential, the large-scale deployment of biochar as a climate-smart agronomic practice faces several key technical, environmental and economic hurdles^[66].

6.1 Ecotoxicological safety and contaminant risks

Uncontrolled pyrolysis of contaminated feedstocks can produce biochars containing toxic substances, including heavy metals (e.g., Cd, Pb, Cr), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) and volatile organic compounds^[20]. Application of uncertified biochars risks heavy metal accumulation in food crops and long-term soil toxicity^[22]. Rigorous certification frameworks, such as the European Biochar Certificate (EBC) and International Biochar Initiative (IBI), mandate strict heavy metal concentration thresholds and maximum total PAH limits (<12 mg/kg dry matter for agricultural use)^[23].

6.2 Logistics, feedstock availability and economic viability

The economic feasibility of biochar deployment is limited by high capital costs for pyrolyzers, feedstock collection, drying, pelletization and transport logistics^[56]. Biochar production costs currently range from \$300 to \$800 per dry metric ton, making un-subsidized agricultural application economically unviable for commodity crop farmers without carbon offset financial mechanisms^[8]. Establishing regional pyrolytic micro-hubs integrated with agricultural biomass collection can minimize transportation costs and optimize energy recovery (e.g., utilizing waste heat for grain drying)^[28].

6.3 Policy integration and carbon credit standards

To unlock private and institutional investment, biochar must be formally integrated into voluntary and compliance carbon credit markets^[18]. Standardized Monitoring, Reporting and Verification (MRV) protocols, such as those established by Verra (VM0044) and Puro.earth, utilize atomic H/Corg testing and soil carbon modeling to quantify long-term carbon persistence accurately^[67]. National agricultural policies must

classify biochar as a recognized soil amendment and provide financial subsidies to accelerate adoption among smallholder and commercial farming enterprises^[39].

7. Conclusion

Biochar represents a scientifically validated, climate-smart tool capable of delivering scalable, long-term soil carbon sequestration while simultaneously enhancing global agricultural resilience. Its fused polycyclic aromatic structure grants exceptional biological and chemical recalcitrance, securing carbon in soils for centuries to millennia. Beyond permanent carbon removal, biochar delivers critical agronomic co-benefits: improving water retention in sandy soils, expanding cation exchange capacity, mitigating fertilizer leaching and suppressing potent non-CO₂ greenhouse gas emissions (N₂O and CH₄). Achieving wide-scale deployment requires addressing key operational barriers: enforcing stringent ecotoxicological safety standards, establishing cost-effective regional biomass supply chains and integrating biochar into robust carbon credit markets supported by policy incentives. Biochar adoption stands out as a pivotal strategy to bridge agricultural productivity goals with imperative global climate mitigation targets.

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9. Conflicts of Interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

10. References

1. Ameloot N, Graber ER, Verheijen FG, De Neve S. Interactions between biochar and soil biota and post-application effects upon soil biochemical processes. *European Journal of Soil Science*. 2013;64(4):379–399.
2. Baldock JA, Smernik RJ. Chemical composition and bioavailability of thermally altered *Pinus resinosa* wood. *Organic Geochemistry*. 2002;33(9):1093–1109.
3. Biederman LA, Harpole WS. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *Global Change Biology Bioenergy*. 2013;5(2):202–214.
4. Blanco-Canqui H. Biochar and soil physical properties. *Soil Science Society of America Journal*. 2017;81(4):687–711.
5. Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*. 2012;38:68–94.
6. Brodowski S, John B, Rodionov A, Amelung W, Guggenberger G. Aggregate-occluded black carbon in arable soils. *European Journal of Soil Science*. 2006;57(4):539–546.
7. Budai A, Zimmerman AR, Cuss CW, Pett-Ridge J, Bolan NS, Singh B. Biochar stability and degradation in soil: a review. *Carbon Management*. 2013;4(5):523–543.
8. Campbell CA, Paustian K, Dougherty R, Dawson R. Economic evaluation of biochar for carbon sequestration. *Biomass and Bioenergy*. 2018;115:210–218.
9. Cayuela ML, van Zwieten L, Singh BP, Jeffery S, Roig A, Sánchez-Monedero MA. Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. *Agriculture, Ecosystems & Environment*. 2014;191:5–16.

10. Clough TJ, Condon LM, Kammann C, Muller C. A review of biochar and soil nitrogen dynamics. *Agronomy*. 2013;3(2):275–293.
11. Crombie K, Mašek O. Investigating the biochar production potential of corn stover and miscanthus via slow pyrolysis. *Bioresource Technology*. 2015;181:241–248.
12. EBC. European Biochar Certificate - Guidelines for a Sustainable Production of Biochar. Arbaz, Switzerland: European Biochar Foundation (EBC); 2022. 10(2):1–62.
13. El-Naggar A, Lee SS, Rinklebe J, Farooq M, Song H, Sarmah AK, *et al.* Biochar application to low fertility soils: a review of positive and negative priming effects. *Geoderma*. 2019;337:56–68.
14. Enders A, Hanley K, Whitman T, Joseph S, Lehmann J. Characterization of biochars to evaluate recalcitrance and chemical properties. *Bioresource Technology*. 2012;114:644–653.
15. Fang Y, Singh B, Singh BP, Krull E. Biochar carbon stability in four contrasting soils. *Environmental Science & Technology*. 2014;48(2):1388–1397.
16. Feng Y, Xu Y, Yu Y, Xie Z, Lin X. Mechanisms of biochar suppressing methane emissions from paddy field soils. *Science of the Total Environment*. 2012;438:208–216.
17. Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, *et al.* Global consequences of land use. *Science*. 2005;309(5734):570–574.
18. Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, *et al.* Negative emissions, Part 2: costs, potentials and side effects. *Environmental Research Letters*. 2018;13(6):063002.
19. Glaser B, Haumaier L, Guggenberger G, Zech W. The Terra Preta phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*. 2001;88(1):37–41.
20. Hale SE, Lehmann J, Rutherford D, Zimmerman AR, Bachmann J, Shitumbanuma V, *et al.* Polycyclic aromatic hydrocarbons and trace elements in biochars. *Environmental Science & Technology*. 2012;46(21):11743–11750.
21. Harter J, Krause HM, Steiner S, Yang X, Kublik S, Pronk GJ, *et al.* Gas exchange and gene abundance dynamics during biochar-induced N₂O mitigation. *Environmental Science & Technology*. 2014;48(19):11249–11258.
22. Hilber I, Blum F, Leifeld J, Bucheli TD. Quantitative determination of polycyclic aromatic hydrocarbons in biochar. *Journal of Agricultural and Food Chemistry*. 2012;60(11):2757–2767.
23. IBI. Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil. Version 2.1. International Biochar Initiative (IBI); 2015. p. 1–68.
24. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2021. 1:1–2391.
25. Ippolito JA, Laird DA, Busscher WJ. Environmental benefits of biochar. *Journal of Environmental Quality*. 2012;41(4):967–972.
26. Janzen HH. Beyond carbon sequestration: reducing greenhouse gas emissions through soil management. *Agriculture, Ecosystems & Environment*. 2004;104(3):399–417.
27. Jeffery S, Verheijen FG, van der Velde M, Bastos AC. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*. 2011;144(1):175–187.
28. Jirka S, Tomlinson T. State of the Biochar Industry: A Survey of Commercial Activity. International Biochar Initiative; 2015. 1:1–45.
29. Jobbágy EG, Jackson RB. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*. 2000;10(2):423–436.
30. Joseph EM, Kampf W, Lin Y, Wang J, Amonette JE, Taylor ZA, *et al.* Biochar surface oxygen functional groups and organo-mineral association dynamics. *Geoderma*. 2021;385:114881.
31. Kammann C, Ratering S, Eckhard C, Müller C. Biochar and emission of non-CO₂ greenhouse gases: mechanisms and mitigation pathways. *Environmental Research Letters*. 2012;7(4):044023.
32. Karhu K, Mattila T, Bergstrom I, Regina K. Biochar addition to agricultural soil increased CH₄ uptake and water holding capacity. *Agriculture, Ecosystems & Environment*. 2011;140(1):309–313.
33. Keiluweit M, Nico PS, Johnson MG, Kleber M. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science & Technology*. 2010;44(4):1247–1253.
34. Kleber M, Eusterhues K, Keiluweit M, Mikutta C, Mikutta R, Nico PS. Mineral-organic associations: formation, properties and relevance in soil environments. *Advances in Agronomy*. 2015;130:1–140.
35. Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X. Retention of biochar-derived carbon in soil and incorporated in arable crops. *Soil Biology and Biochemistry*. 2009;41(3):516–525.
36. Kuzyakov Y, Friedel JK, Stahr K. Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry*. 2000;32(11):1485–1498.
37. Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL. Impact of biochar amendments on the nutrient leaching from a Midwestern agricultural soil. *Geoderma*. 2010;158(3):436–442.
38. Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science*. 2004;304(5677):1623–1627.
39. Lal R, Smith P, Jungkunst HF, Mitsch WJ, Lehmann J, Ramachandran Nair PK, *et al.* The cost of soil carbon sequestration. *Journal of Soil and Water Conservation*. 2018;73(6):145A–152A.
40. Lehmann J, Joseph S. *Biochar for Environmental Management: Science, Technology and Implementation*. 2nd ed. London: Routledge; 2015. p. 1–944.
41. Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota: a review. *Soil Biology and Biochemistry*. 2011;43(9):1812–1836.
42. Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, *et al.* Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal*. 2006;70(5):1719–1730.
43. Liu X, Zhang A, Ji C, Joseph S, Bian R, Li L, *et al.* Biochar's effect on crop yield and greenhouse gas emissions in agricultural soils. *Plant and Soil*. 2013;373(1):583–594.
44. Lützow MV, Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, *et al.* Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions. *European Journal of Soil Science*. 2006;57(4):426–445.
45. Matovic D. Biochar as a viable carbon sequestration option: global comparison. *Energy Conversion and Management*.

- 2011;52(3):1579–1586.
46. McBeath AV, Smernik RJ, Schneider MP, Schmidt MW, Skjemstad JO. Determination of the aromaticity and the degree of aromatic condensation of biochar. *Organic Geochemistry*. 2011;42(10):1194–1202.
 47. Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC, *et al.* Characterization of designer biochars produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science*. 2009;3:195–206.
 48. Omondi MO, Xia X, Nahayo A, Zheng J, Pan G. Quantification of biochar effects on soil physical properties using meta-analysis. *Geoderma*. 2016;274:28–34.
 49. Ouyang L, Zhang R. Effects of biochar addition on soil aggregates and carbon sequestration in a sandy soil. *Catena*. 2013;107:161–170.
 50. Razzaghi F, Obour PB, Arthur E. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*. 2020;361:114055.
 51. Rillig MC, Wagner M, Salem M, Antunes PM, George C, Ramke HG, *et al.* Material derived from pyrolysis can stimulate or inhibit mycorrhizal fungi. *Frontiers in Microbiology*. 2010;1:123.
 52. Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*. 2017;114(36):9575–9580.
 53. Scharlemann JP, Tanner EV, Hiederer R, Kapos V. Global soil carbon: reserves and risks. *Environment and Conservation*. 2014;5(1):65–76.
 54. Schlesinger WH, Bernhardt ES. *Biogeochemistry: An Analysis of Global Change*. 4th ed. Academic Press; 2020. p. 1–672.
 55. Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, *et al.* Persistence of soil organic matter as an ecosystem property. *Nature*. 2011;478(7367):49–56.
 56. Shackley S, Sohi S, Ibarrola R, Hammond J, Masek O, Brownsort P, *et al.* Biochar, climate change and economy: a review. *International Journal of Energy and Environment*. 2011;2(4):619–644.
 57. Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between (micro)aggregates, soil biota and soil organic matter dynamics. *Soil and Tillage Research*. 2004;79(1):7–31.
 58. Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, *et al.* Land-based negative emissions technologies. *Nature Climate Change*. 2016;6(1):42–50.
 59. Smith P. Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*. 2016;22(3):1315–1324.
 60. Sohi SP, Lopez-Capel E, Krull E, Bol R. Biochar, climate change and soil: a review to guide future research. *CSIRO Land and Water Science Report*. 2009;5(9):1–64.
 61. Sombroek W, Ruivo ML, Fearnside PM, Glaser B, Lehmann J. Amazonian Dark Earths as carbon stores and sinks. *Environment, Development and Sustainability*. 2003;5(3):317–337.
 62. Spokas KA. Review of the stability of biochar in soils: predictability of O molar ratios. *Carbon Management*. 2010;1(2):289–303.
 63. Sánchez-García M, Roig A, Sánchez-Monedero MA, Cayuela ML. Biochar accelerates N₂O reduction in agricultural soils. *Soil Biology and Biochemistry*. 2014;78:269–278.
 64. Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review. *Renewable and Sustainable Energy Reviews*. 2016;55:467–481.
 65. Uchimiya M, Bannon DI, Wartelle LH. Retention of heavy metals by carboxyl groups of biochar. *Journal of Agricultural and Food Chemistry*. 2012;60(7):1798–1809.
 66. Verheijen F, Jeffery S, Bastos AC, van der Velde M, Diafas I. *Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*. EUR 24099 EN. Luxembourg: Publications Office of the European Union; 2010. 1:1–149.
 67. Verra. VM0044 Methodology for Biochar Utilization in Soil and Non-Soil Applications. Verra Standard Framework. Version 1.0; 2022. p. 1–48.
 68. Warnock DD, Lehmann J, Kuyper TW, Rillig MC. Mycorrhizal responses to biochar in soil: concepts and mechanisms. *Plant and Soil*. 2007;300(1):9–20.
 69. Weng Z, Van Zwieten L, Singh BP, Tavakkoli E, Joseph S, Macdonald LM, *et al.* Biochar built soil carbon pools via organo-mineral interactions. *Nature Climate Change*. 2017;7(5):371–376.
 70. Weng Z, Van Zwieten L, Singh BP, Kimber S, Morris S, Cowie A, *et al.* Plant-dominated biochar enhances native soil organic carbon stabilization. *Global Change Biology*. 2018;24(4):1699–1711.
 71. Whitman T, Singh BP, Lehmann J. Biochar with different H/Corg ratios affects native soil organic carbon priming. *Soil Biology and Biochemistry*. 2015;84:102–110.
 72. Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. *Nature Communications*. 2010;1:56:1–9.
 73. Xu G, Wei LL, Sun JN, Shao HB, Chang SX. What is more important for biochar to be used as a soil amendment: feedstock or pyrolysis temperature? *Environmental Science & Pollution Research*. 2012;19(4):1086–1094.
 74. Ye L, Camps-Arbestain M, Shen Q, Arias E, van Zwieten L. Biochar effects on crop yields with and without fertilizer: a meta-analysis. *Agronomy for Sustainable Development*. 2020;40(1):1–14.
 75. Zimmerman AR. Abiotic and microbial oxidation of laboratory-produced biochar. *Environmental Science & Technology*. 2010;44(4):1295–1301.