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Biochar

PERSPECTIVE

Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible

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Abstract

Science should drive policies and regulations to ensure a sustainable (environmentally, socially, and economically) green transition to a Net-Zero / Net-Negative circular economy. Since 2015, which saw COP21 in Paris, Net Zero has been a global target that must be rapidly accompanied by a Net Negative strategy to mitigate climate change. Accordingly, biochar's role as a durable carbon removal method is gaining attention and increasing. In this work, we discuss the durability of the carbon in biochar and the need for analytical techniques to support stakeholders on a project level. The different ecologically relevant groups of carbon forms contained in biochar are presented, and possible project-based methods to assess the quality and durability of the product versus the regulatory requirements for the permanence of carbon removals are summarized. Biochar is today one of the CDR technologies with the highest technology readiness level (TRL 8–9) that can ensure permanent removals for time frames relevant to climate change mitigation projects, combined with co-benefits that are gaining relevance in terms of mitigating climate impacts in agricultural soils.

Abstract Highlights

- Biochar comprises different carbon forms, for which permanence is discussed here.
- Biochar can deliver cost-effective long-term Carbon Dioxide Removal (CDR), which is possible to deploy at large scale.
- Project-level Biochar Carbon Removal (BCR) can be verified by analytical techniques and third-party certification.
- Certified BCR can be accounted towards nation-wide climate targets.
- Site-specific co-benefits can be generated, supporting the shift to more sustainable and climate-resilient agriculture

Keywords Biochar carbon removal, Carbon dioxide removal

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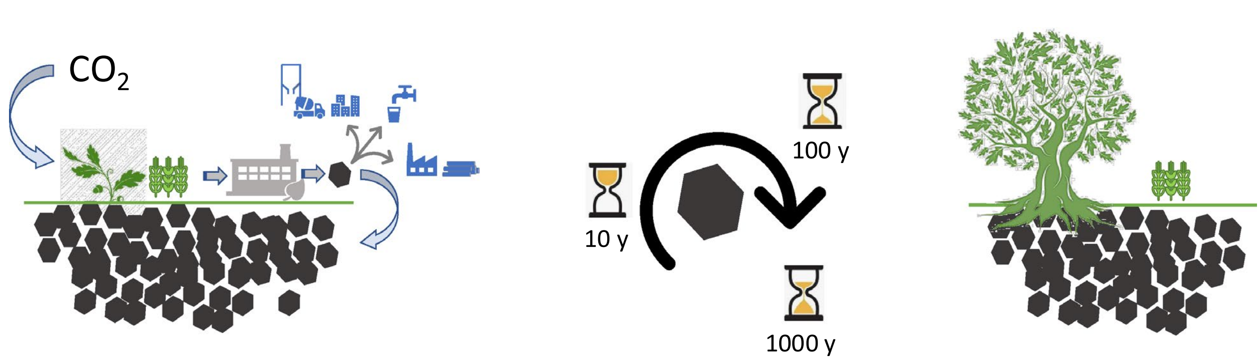
Graphical Abstract



1 Introduction and scope

Carbon Dioxide Removal (CDR) is recognized as essential elements of a global strategy to achieve the climate targets set for 2030 and 2050. The aim is to limit global warming to below 2 °C by the end of the century, preferably below 1.5 °C. Accurate quantification, tracking and certification of the amount of carbon removed from the atmosphere are essential for credible and long-lasting action.

CDR can be implemented through various techniques, such as Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture and Storage (DACS), or Biochar Carbon Removal (BCR). The scope of this work is to critically evaluate biochar as carbon removal method, and its permanence in soil.

2 Biochar in soil: a form of long-lived carbon dioxide removal

2.1 Biochar for carbon dioxide removal

BCR is the most technically advanced and scalable permanent CDR solution at present and for the foreseeable future: it accounted for 87% of all permanent carbon removal deliveries in the voluntary carbon market, at by far the lowest cost of any alternative durable carbon removal solution (cdr.fyi 2024). Additionally, BCR provides co-benefits that most industrial CDR options do not offer: first of all, supporting the transition to regenerative agriculture and sustainable forestry, but also supporting the adaptation of agriculture to climate impacts as well as offering new opportunities for socio-economic development, such as new income opportunities (from possible carbon credits) or continued farming in marginal areas after soil restoration with sustainable agricultural practices (among which, biochar is used as a soil amendment).

Studies available in the scientific literature (Paustian et al 2016; Bossio et al 2020; Lehmann et al 2021; Roe et al 2021; Lefebvre et al 2023) provide estimates of the significant contribution that biochar can offer to CDR at the global scale. The total CO_2 removal potential in the European region is estimated at 133 million tons CO_{2eq} per year (Roe et al 2021). Assuming a conversion rate of 2.7 t of CO_2 per t of biochar, the EU Biochar Industry estimated carbon dioxide removals to increase to 6 million tons of CO_2 in 2030, and almost 100 million tons of CO_2 in 2040 (EBI, 2023). This requires maintaining a challenging but possible 70% growth rates.

The biochar approach is highly feasible compared to other land-based CDR strategies. In fact, BCR is a readily available and scalable technology with a high Technology Readiness Level (TRL) of 8–9 (as shown by cited market reports and industrial experience with hundreds of biochar production plants operating worldwide).

Also, BCR can be tracked, certified and accounted for utilizing certification systems that are based on sound evidence and product measurements, such as Puro Earth (Puro Earth, 2024a) , Verra (Verra, 2023) or Gold Standard and others (IBBN, 2024). CDR standards with biochar methodologies already exist that provide rigorous accounting for sustainable net removals, such as Puro. Earth 2024b). Verra (2024), EBC (2021). Digital MRV (Monitoring, Reporting and Verifying) providers offer tracking of biochar and carbon end use (such as Carbonfuture 2024).

2.2 Natural pathways of carbon sequestration and storage: from biosphere to geosphere

In general, the Earth utilizes two natural pathways to remove carbon dioxide from the atmosphere, subsequently sequestrating and storing carbon from biosphere into geosphere. The first pathway involves the chemical processing of dissolved CO_2, which leads to precipitation of carbon dioxide in the form of carbonates. It accounts for approximately 64 million gigatons of carbon stored in the geosphere. This process is also referred to in geology as mineralization. It is worth to remark how this term has different meanings depending on the considered scientific field. While in case of geology and CDR technologies it refers to the formation of carbonates from CO_2 (i.e., a CO_2 removal process effectively storing CO_2 in a solid carbonate minerals), in soil science and carbon cycle science "organic carbon mineralization" means the decomposition of organic matter and the release of CO_2 through microbial metabolization.

The second pathway is the sequestration of CO_2 through photosynthesis into biomass and the preservation of a selected fraction of the carbon in biomass via a long-term geological process known as "organic carbon maturation." This process encompasses biological and/or thermal alterations of carbon in biomass, gradually carbonizing the organic matter. It involves the progressive loss of hydrogen, oxygen, and other volatiles, and the enrichment of carbon in the form of highly aromatized and condensed macromolecules. These macromolecules, essentially inaccessible for surface and low-temperature Earth carbon cycle processes, are thus considered permanently stored. The highly carbonized form of organic carbon molecules is known as an "inertinite" maceral. This process accounts for over 15 million gigatons of carbon stored in the geosphere, dwarfing the entire mass of carbon in the biosphere—47,000 gigatons. This total includes carbon dioxide in the atmosphere (750 gigatons), organic carbon in all terrestrial vegetation (450 gigatons), and dissolved carbon in the ocean (40,000 gigatons). Organic petrologists refer to the process of organic carbon maturation as maceralization. This process can be accelerated artificially through high-temperature carbonization using pyrolysis techniques, which fast tracks the slow geological maturation by rapidly aromatizing and condensing the organic carbon molecules. If it has gone through a complete carbonization process, the resulting biochar has attained properties akin to inertinite that make it difficult to be metabolized by microorganisms.

Naturally, pre-anthropogenic occurrences of wildfires in oxygen-depleted environments have led to the production of naturally occurring char or inertinite macerals. These are commonly found in sedimentary rocks of various ages and depositional environments. The frequent occurrence of inertinite produced from wildfires in sedimentary rocks, shallow bed, and outcrops, which have been exposed to atmospheric oxygen for millions of years before their deposition and burial in sedimentary basins or later due to uplift as outcrops, serves as solid evidence of the long permanence of inertinite.

While fungi and bacterial degradation of biochars over long periods of time occurs, thoroughly pyrolyzed biochars have been found in the archaeological record to remain in soils well beyond millennial timescales. More extended discussion related on this section can be found in literature (Sanei et al. 2024).

2.3 Biochar persistence in the environment

Solid scientific evidence confirms biochar's persistence in the environment over long periods of time (long-lived carbon sequestration). Among others, the European Commission Joint Research Center (JRC) carried out a detailed and evidence-based assessment of the long-lived carbon removal nature of biochar (European Commission JRC, 2023; Schievano 2023), as also found in the Terra Preta case, where carbon was still present after many centuries. Today all this is well known and demonstrated, based on experimental evidence and broadly described in the scientific literature that JRC reported in its meta-analysis (such as Wang et al. 2016; Lehmann et al. 2021; Woolf et al. 2021). Methods for calculating permanent biochar carbon have been included in the national greenhouse gas accounting report published in 2019 by the Intergovernmental Panel on Climate Change (IPCC) and in 2024 by the United States Department of Agriculture (Ogle et al. 2024). Other methods are accepted as the basis for carbon trading platforms on the existing voluntary carbon markets.

IPCC' s guidance is recognized as a meta study that most institutions and governments rely on. The 2022 report and the IPCC report on National Greenhouse Gas Accounting argue that the fused aromatic ring structure generated by pyrolysis reduces the microbial decomposition of the plant-derived carbon matrix of biochar to an extent that it can be considered a permanent terrestrial carbon sink relevant for climate change mitigation. The decomposition rates of the resulting biochars are orders of magnitude slower than the biomass from which it is produced. This results in biochar-type carbons typically being the oldest fractions of soil organic carbon, with often several thousand years old C-14 dates (Pessenda et al. 2001).

Evidence also exists from the recent application of techniques well-known in geological studies that the least degradable organic carbon fraction in biochar can reach properties and characteristics that can be considered highly durable over time scales exceeding hundreds of years (Petersen et al. 2023).

2.4 Soil carbon accumulation and sustainable biofuels

The accumulation of Soil Organic Carbon, SOC (also indicated with the acronym SCA, Soil Carbon Accumulation) has been addressed at the EU level in the calculation of the GHG performance of the feedstock used in sustainable biofuels production. Among the agricultural practices that generate carbon removals in farming, accounted for in the parameter "Esca" of the REDII, biochar is included, with the highest possible threshold (45 gCO_2 MJ^{-1}). Thus, the sustainable production of biochar from crop and process residues can also improve soil health as well as the GHG balance of the biofuel, returning carbon to the soil. Other international institutions dealing with sustainable fuels for aviation and maritime use are discussing a similar methodology.

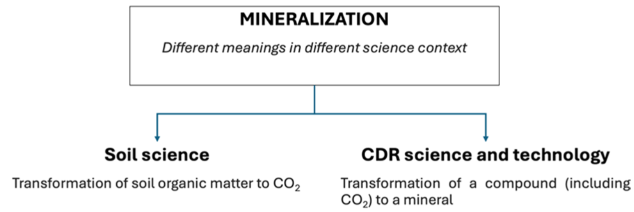


Fig. 1 Mineralization in Soil and CDR science

2.5 Biochar carbon sequestration

The short-term decomposition of biochar is dominated by microbial metabolization of organic carbon forms that do not resemble fused aromatic ring structures. Since the available laboratory and field studies that have been used to quantify the mean residence times of biochars are constrained to only a few years to less than 10 years, and in most cases about one year (Lehmann et al. 2015; Woolf et al. 2021), these estimates are biased by what is expected to be decomposed over short periods of time. Despite this, studies have indicated degradation rates of the most stable carbon pool in the order of 0.0018% $year^{-1}$ (compared to an easily mineralizable C pool with a degradation rate of 0.0093% day^{-1}): this corresponds to more than 550 years mean residence time. Similar conclusion was reported based on a study utilizing a biogeochemical field model (Jianxiang Y et al. 2022). This level of decomposition and, thus, the release of CO_2 into the atmosphere is comparable to acceptable leakage rates considered for CCS, depending on poor- or well-regulated characteristics of onshore/offshore storage (regional storage security decreasing from well-regulated to poorly-regulated) (Alcade et al. 2018). See Fig. 1.

Predicting carbon persistence based on extrapolation from relatively short-term incubation of biochar consisting of a rapidly degrading carbon mixed with highly persistent one will always result in large uncertainties. However, while the absolute determination of the durable carbon fraction in biochar with high-level accuracy is currently not feasible, numerous available and cost-effective analytical techniques exist that allow benchmarking of biochar permanence against agreed standards at the project level with sufficient accuracy. In fact, combining former studies with the most recent research, according to applicable norms, a set of well-known laboratory analyses emerged as credible proxies for determining how much of the carbon is effectively retained in biochar in a long-lasting form. These methods can thus be used to characterize biochar products by commercial operators. Among these, the Hydrogen to Organic Carbon ratio, the Random Reflectance (Ro) analysis and the Fixed Carbon measurements show very high correlation (Sanei et al. 2024) with biochar decomposition data, and thus can be considered suitable for monitoring and verification purposes.

A growing volume of industry data and scientific evidence increases the confidence in such assessments of biochar durability. A recent study showed that 93% of 27 industrially produced biochar (mostly above 500 °C for longer residence time) showed a H/C ratio below 0.4, associated with well-carbonized biochar. Furthermore, the use of the random reflectance method (Ro call) provided further helpful information on these biochars, enabling the differentiation of biochar with different types of inertinite-like carbon. These recent findings showing that biochars contain organic carbon akin to the most persistent geological macerals of inertinite land further support the claim of a permanent sink for climate change mitigation, defined here (in line with proposed EU Carbon Removal Certification Framework-CRCF) as from several centuries to several millennia (Sanei et al 2024; Petersen et al 2023).

3 Multiple co-benefits of biochar for the environment and the society

Biochar can, in addition to its role in climate change mitigation, also play a key role in restoring soil health, promoting water retention and crop resilience towards changing precipitation regimes and extreme weather events, creating conditions conducive to microbiological life and biodiversity in soil, and supporting socioeconomic development in rural areas. The area of agricultural soils in Europe that are low in Soil Organic Carbon (SOC) is so large that since 2018 the European Commission has already been called by the European Court of Auditors (EU Court of Auditors, 2018) to step up its strategy against desertification and land degradation. Officially starting 2021, the EU Commission has established the EU Mission "A Soil Deal for Europe" to tackle these problems (European Commission Soil Deal, 2024).

Agronomic benefits (Schmidt et al 2021) have been extensively investigated and assessed: these depend on local agro-climatic and pedo-climatic conditions.

On average, the more degraded the soils are, the more evident the benefits from biochar and other organic amendments, including co-composted biochar and organic matter (Casini et al 2021). Biochar addition, together with other forms of regenerative agriculture practices (compost, no tillage, cover cropping, use of digestates from farm-scale anaerobic digestion, etc.), are recognized as sustainable agricultural practices in the REDII-Implementing Regulation, thus key elements of a green transition of agriculture, consistent with the Green Deal and the Farm to Fork EU policy. These are co-benefits of CDR obtained through biochar addition in soils, which makes the biochar proposition unique compared to industrial CDR solutions and by far the most doable and cost-effective in both the short and the medium/long term.

In addition to its applications in soils, biochar can be used as a partial replacement for cement in concrete, one of the world's highest-emitting hard-to-abate industries. It can add value to concrete by improving strength, soundproofing and thermal insulation while reducing weight (Gupta et al. 2020; Khitab et al 2021; Lin 2023). Incorporated into the concrete matrix, the stored carbon dioxide is permanently sequestered, offsetting C emissions—and with the potential to transform a formerly high emitting sector into an active carbon sequestration industry. Carbon fractions can also be incorporated into steel, depending on the type of steel-making process and how biochar is used.

4 Conclusions

Based on the rationale presented in this paper, biochar, when produced from certified sustainable feedstock and according to existing product standards, possesses all the requirements to ensure durability, i.e., long-term CDR when used in soil and other applications. The potential for BCR is on a billion tonnes scale globally and has significant regional potential in many parts of the world compared to other nature-based climate solutions (Roe et al 2021). This together with the different potential soil benefits, particularly in those areas where soil is sandy and acidic and where moisture is limiting plant growth, supports the necessary shift to regenerative and more resilient agriculture.

Based on the solid scientific evidence developed over the last decade, some of which is summarised here, biochar should thus be considered as a key CDR technology, diversifying the portfolio of readily available and high TRL (Technology Readiness Level) climate change mitigation options.

Author contributions
All authors contributed to the study's conception and design, material preparation, data collection, and analysis. David Chiaramonti wrote the manuscript's first draft and final version; all authors commented on previous versions. All authors read and approved the final manuscript.

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Data availability
No data were used for the research described in the article.

Declarations

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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