

Sustainable Roles of Biochar in Carbon Sequestration and Climate Change Mitigation

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Abstract. Biomass agricultural waste can be pyrolyzed to produce a lateral carbon load carbon-rich biochar. The world is becoming increasingly interested in this resource, which is done by the two major challenges, namely climate change and resource management. Biochar is a long-term carbon sink because it stabilizes organic carbon such that it can remain unaltered cyclically across millennia, contributing unambiguously negative emissions. Empirical evidence has constantly revealed that biochar has positive agronomic effects, due to its potential to increase the fertility of the soil, conservation of natural water, as well as the inhibition of several gas emissions such as methane and nitrous oxide. Therefore, biochar will not only enhance production but will also improve the environmental situation, and finally, productivity will increase. In addition, well-thought-out uses of biochar in both construction, one of the managements of waste, and various environmental cleanup have demonstrated its potential in a twofold way as a versatile agent and as the one that maintains continuous carbon uptake. Regardless of its favorable qualities, there are obstacles related to the problems of scale, mass-scale production, and the creation of a framework of regulations. The paper explores the many functions biochar has led in sustainable agriculture, circular economies and climate-action solutions by arguing that biochar can be established as a milestone technology to global sustainability and long-term resilience.

Keywords: Biochar, Carbon sequestration, Climate change mitigation, Soil stability, Greenhouse gas emissions.

1. Introduction

Climate change, which is mainly due to accumulations of greenhouse gases like CO₂, is now one of the most serious threats to evening global ecosystems, world food security, and man's way of life [1]. Global warming caused by the ongoing increase in atmospheric CO₂ levels (primarily due to the burning of fossil fuels and deforestation) has resulted in extreme weather events; and a threat to agricultural production or even human survival. Consequently, strategies of minimizing net emissions and maximizing the level of carbon sequestration have assumed emergency status.

The biggest carbon sink on the land, soil is in a great position to absorb CO₂ long-term [2]. Another promising solution is biochar, a product of the pyrolysis (heating biomass in the absence of

oxygen) of biomass that contains a lot of carbon. It is a big proponent of the United Nations Sustainable Development Goals on climate action (SDG 13), hunger (SDG 2), and clean water (SDG 6) [3]. Its porous and yet stable structure causes it to endure decades, maybe even centuries in soils enhancing their fertility, holding water and cycling nutrients.

Biochar is no longer a concept but a reality due to technological advances. The world output has already surpassed the 350,000 ton mark every year and the market is valued at 763 million dollars in 2024. This is expected to triple by the year 2032 [4]. It has been established by field research to have agronomic benefits: they found an average increase of 5-16 percent in the yield, a decrease in the emission of both methane (-13.5 percent) and nitrous oxide (-21.4 percent), and an increase in the amount of soil organic carbon (+52.5 percent) [5]. These findings indicate that biochar contributes to climate mitigation and agricultural sustainability in two aspects. But some of the issues that it still experiences are standardization, scaling up and cost. The review concentrates on the opportunities of a long-lasting capture of carbon and reduction of greenhouse gases with biochar and the limitations of biochar and the research that needs to be done.

2. Biochar properties

Biochar is a carbon-rich solid produced by the thermochemical transformation of biomass, typically in the absence or limited supply of oxygen. It is commonly referred to as a charcoal-like material with high carbon content, created through the thermal breakdown of organic materials such as plant residues or wood, under oxygen-limited conditions. This process (usually pyrolyzed at ~700 °C) is excluded the fossil fuel-derived materials as raw materials [3]. Conventional charcoal and other carbonaceous materials of similar kinds are used for combustion while the biochar is for the soil application. Biochar is intended to ameliorate the soil physicochemical and biological properties as well as to get the net sequestration of carbon in the long run. The physicochemical characteristics of biochars (carbon content, hydrogen to carbon ratio, pH, cation exchange capacity (CEC) and nutrient concentrations (e.g., N, P, K)) determine their environmental functions. The hotter the pyrolysis temperature, the more aromaticity and less of the labile fraction and volatile matter--this tends to suggest that the stability is enhanced; nutrient availability is higher [6]. Biochar pyrolyzed at lower temperature is likely to hold more of the different functional groups and plant available nutrients, hence the soil is likely to be more productive, but will decompose quickly. This makes biochar durable carbon sink-cum soil benefits which can enhance the fertility, water retention and adsorption of pollutants. The reason is its wide applications and why people are beginning to use it more not only in cultivation but also in repairing and remediation of the environment.

3. Biochar feedstock and production

The yield and characteristics of the resulting product are primarily influenced by three main factors (Table 1). Generally, slow pyrolysis (300-700°C), hours to days, less than 1 °C /s) maximizes solid yield (~35%), intermediate pyrolysis (500-650 °C) increases bio-oil production (~50%), and fast and flash pyrolysis favor liquid and gas production [7,8]. Different structures and functionalities are obtained by other methods, including gasification and hydrothermal carbonization (HTC), as shown in Table 1.

Table 1. Pyrolysis types and products of pyrolysis processes in different conditions [9,10,11]

Process	Temperature (°C)	Residence Time	Heating Rate (°C/s)	Yields (%)		
				Biochar	Bio-Oil	Syngas
Slow pyrolysis	300–700	hours–days	<1	35	30	35
Fast pyrolysis	300–1250	0.5–20 s	10–200	12	75	13
HTC	180–300	1–16 h	–	50–80	5–20	2–5

The physico-chemical properties of biochar depend on the nature of feedstock and operational temperature of pyrolysis process, as shown in Table 2. As an example, woody biomass like chips of *Fagus sylvatica* normally contain a carbon ratio of more than 85 % but agricultural waste like stems of *Brassica napus* contain phosphorous in a ratio of up to about 37% [9]. As a rule, the higher pyrolysis temperature, the higher pH and fixed-carbon content and the lower volatile matter and hydrogen content, the closer the material gets to a more stable, carbon-rich state.

The variations in the composition of feedstock and production specifications result in unique physico-chemical properties of biochar such as aromaticity, nutrient-retention capacity, and ash content. These properties define how well the material can be used in agriculture, but more importantly, how well the material can be used as a stable carbon sink, a means of greenhouse-gas reduction, and a secondary pollutant immobilization mechanism within larger environmental contexts.

Table 2. A summary of different biomass sources utilized in biochar production [12]

Biomass Feedstock	Temperature (°C)	pH	Elemental Composition (% , Mass Based)				Ash (%)
			C (%)	N (%)	P (%)	K (%)	
Cotton stalk (<i>Gossypium</i> sp.)	550	9.6–10.3	64.3–71.9	1.1–1.9	0.13	0.7	8.8–19.1
Corn stover (<i>Zea mays</i>)	300–500	7.3–9.8	45.5–78.1	0.3–1.5	-	0.01–0.44	5.7–32.8
Rice husk	350–800	5.1–9.6	38.8–47.8	0.3–5.1	-	-	14.5
Poplar (<i>Populus</i> sp.)	300–800	8.1–8.2	43.8–81.1	1.5–3.9	0.4–2.8	0.66–0.92	32.9
Rapeseed stalk (<i>B. napus</i>)	300–800	-	55.4–65.0	3.3–3.9	-	-	27.8–45.1
Bamboo (<i>Bambusa</i> sp.)	250–800	5.2–10.3	38.3–88.4	0.2–2.6	0.24–2.15	0.30–0.52	3.0–4.7

4. Mechanism of carbon sequestration by biochar

Biochar carbon sequestration consists of both material and soil-mediated processes. On the one hand, pyrolysis transforms labile organic matter characterized by condensed aromatic structures of exceptional chemical recalcitrance directly stabilizing carbon for centuries to millennia. On the one hand, biochar is recalcitrant to degradation once incorporated into soils due to the pore protection, nutrient sorption, mineral association and aggregate formation by the surrounding matrix. These two classes of stabilizing mechanisms are explained in the following sections, first by structural and physicochemical properties of biochar itself and thereafter by soil-mediated stabilization processes occurring at different spatial scales.

4.1. Intrinsic structural stability

The key process through which biochar can contribute to carbon sequestration is in the transformation of the fast-cycling biomass carbon to a highly refractory carbon pool with millennial-scale persistence. Plant- or waste-derived organic matter is converted into a condensed aromatic matrix during pyrolysis, which is rich in C-C and C=C bonds. Such bonds have much greater dissociation energies than polysaccharides or lignin, making biochar much more resistant to microbial and enzymatic degradation. Biochar can thus be used to sequester carbon in the slow cycle (centuries to millennia) rather than the fast cycle (years to decades) and thereby prevent the release of atmospheric CO₂ that would otherwise result in biomass decay.

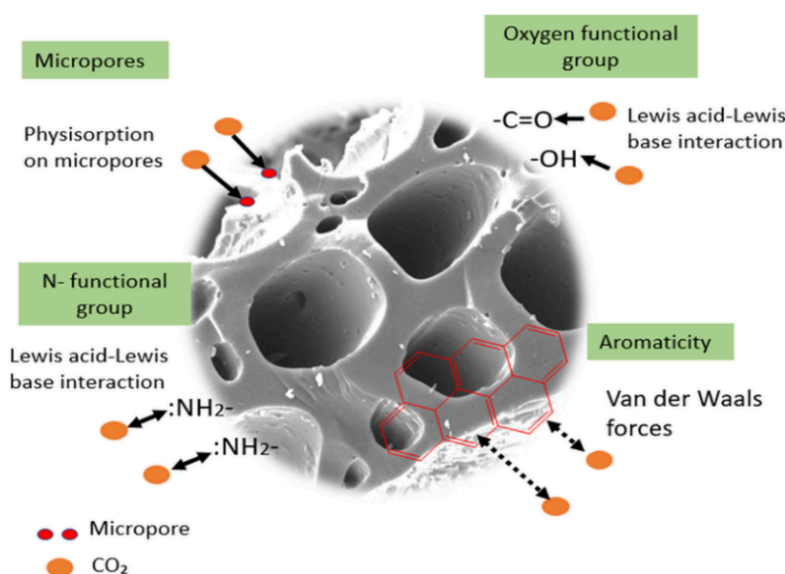


Figure 1. Mechanisms of carbon capture by biochar [13]

In addition to this inherent structural stability, biochar traps CO₂ via a variety of physicochemical interactions, as shown in Figure 1. The microporous structure offers large surface area to physisorbed CO₂ molecules, physically trapping the carbon in nano- and micropores. In the meantime, oxygen and nitrogen functional groups (e.g. -OH, -C=O, NH₂-) help to capture more carbon through Lewis acid-base reactions. The aromatic clusters in the biochar can also stabilize carbon using van der Waals forces, increasing the retention of adsorbed CO₂. These processes together show that biochar does not just prevent a rapid release of carbon but also forms new long-lived storage within soils.

4.2. Soil-mediated stabilization pathways

The protective and adsorptive effects of hierarchical porosity of biochar (micro- to nanopores) stabilize the soil carbon because the porous structure can physically protect labile carbon and slow its decomposition by physically “sheltering” it from microbes by reducing their access; secondly, biochar has large sorption capacity of dissolved organic carbon (DOC) and other reactive soil compounds and sequesters them into more stable pools [14].

Biochar sequesters nitrogen and phosphorus, thus limiting their leaching to reduce microbial priming effects that may otherwise enhance rates of carbon turnover [15]. Moreover, aromatic

carbon was observed to microaggregates in soil by spectroscopic-microscopic analysis, which further supports the physical protection of organic carbon sequestration [15].

Recently, development in 3D imaging technologies can provide quantitative evidence of biochar pores networks. Recent studies showed that biochar has very heterogeneous and interconnected pores, at a variety of scales [16]. Such structural heterogeneity makes the sorption sites more accessible and contributes to the increased ability of biochar to bind organic and inorganic solutes, which makes it a more effective physical barrier and chemical sink.

The stability of carbon from biochar inputs into soil is controlled by the stable carbon structures created during the pyrolysis process: aromatic structures. These can be determined by the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) atomic ratio, which represent carbon's aromaticity and polarity, respectively, the lower the value, the more recalcitrant. Empirical syntheses demonstrate that raising the pyrolysis temperature in a systematic way lowers the H/C and O/C ratio and produces more condensed matrices. A working definition of stability is $H/C < 0.4$ (highly carbonized/aromatic), and many biochars produced at 600°C or higher have $O/C \leq 0.1$; both trends indicate increased chemical stability and decreased degradability [16]. By comparison, a more conservative, commonly used predictive threshold of long-term persistence is $O/C < 0.2$, which is half-lives of biochar carbon in soils of order 1000 years or more [17]. When taken together, these indicators, that is, the H/C and O/C elemental ratios, are more quantitative and production-independent predictors of physical stability than is the general sequestration principle.

Besides the physical protection offered by pore structure, and chemical recalcitrance offered by biochar itself, long-term stability is also achieved through interactions with the surrounding soil matrix (e.g., through mineral associations; the organic carbon of biochar is complexed with mineral oxides; iron and aluminum oxide or precipitation of mineral oxides in conjunction with calcium carbonate, thus forming mineral to organic complexes that are highly resistant to microbial degradation. Through such associations, carbon is well kept in less degradable pools).

In addition, biochar increases microaggregate in the soil. Biochar increases the mass of microaggregate by acting as a nucleus or glue that helps fine soil particles aggregate ($< 250 \mu\text{m}$) mostly through interactions with clay minerals and cations, which cause physical encapsulation of organic carbon. Microaggregate protection slows diffusion of oxygen and avenue of microbes, which prevents carbon mineralization. Empirical studies have also demonstrated that addition of biochar could significantly improve the mass and stability of macro- and meso-aggregates thus increasing the soil organic carbon content in these aggregates [18].

A combination of these stabilization processes within the soil, further enhanced by the chemical inertness and porous physical structure of biochar, creates a multi-scale defense mechanism. The combined stabilization at the pore level, along with mineral bonding and aggregate encapsulation, gives biochar a significant ability to serve as a carbon reservoir in land-based ecosystems.

5. Biochar's role in climate change mitigation

Biochar applications can be generally classified into two main categories: agricultural and non-agricultural. Of these, agricultural uses have emerged as the most significant, driven by the strong interaction between biochar and land ecosystems. This synergy enhances crop yields while also contributing to the reduction of greenhouse gas emissions.

In agrarian economies, biochar doesn't just serve as an extraordinary carbon sink, but also as soils ameliorants, enhancing the nutrient retention, moisture retention, and the organisms inhabiting a specific soil. In addition to agricultural purposes of biochar, the range of non-agricultural purposes of biochar, including waste management, construction, and materials science, is becoming insanely

prominent, so the scope of biochar is spreading to wider sustainability goals. The twin pathways of application demonstrate that biochar cannot be limited to an agricultural supplement- it is a multifaceted tool to reduce climate change and develop resource circle activities, and both traditional and new domains are increasingly in the spotlight.

5.1. Agricultural applications

The biochar usage most commonly is found in the agricultural sector that contributed more than 77 percent of the world biochar market in 2023 [5]. This preeminence is an indication of the central position of biochar in agricultural practice, as a longer-lasting carbon reservoir that is also an effective source of greenhouse gas (GHG) reduction and soil fertility improvement. In the past, large amounts of agricultural waste and crop residues were directly burned to produce domestic or industrial fuel or left in open fields. Although these sources provide an immediate source of energy, the sources also simultaneously release substantial amounts of CO_2 , CH_4 , N_2O , and black carbon, further contributing to global warming and atmospheric pollution. Conversely, these residues can be transformed to biochar and used in soils to counter such emissions and store a significant portion of carbon in a recalcitrant state over millennial period. Long-term modeling studies have also supported this trade-off, showing that sustainable use of biochar can lead to greater net avoided GHG emissions than simple combustion in all situations investigated in simulations (Figure 2).

Agronomically, biochar also increases soil fertility through increased cation-exchange capacity, nutrient retention, and water-holding capacity, and thus lessens the number of chemical fertilizers required to be used. The resultant reduction in the use of fertilizers also suppresses the agricultural N_2O emissions and strengthens crop production. It has been reported through field experiments that biochar applications can reduce CH_4 emission in paddy systems by 10-40% and N_2O emission in croplands by 15-50% and that it can also increase yield of major cereal crops like maize, wheat and rice by 5-20%. Meta-analytical reviews project that biochar can decrease N_2O emissions by as much as 54% on average and in some controlled environments, may annihilate CH_4 emissions completely [21]. Therefore, biochar is a synergistic remedy, as it can turn waste materials in agriculture into an asset that will help in sustainable farming activities and at the same time curb climate change.

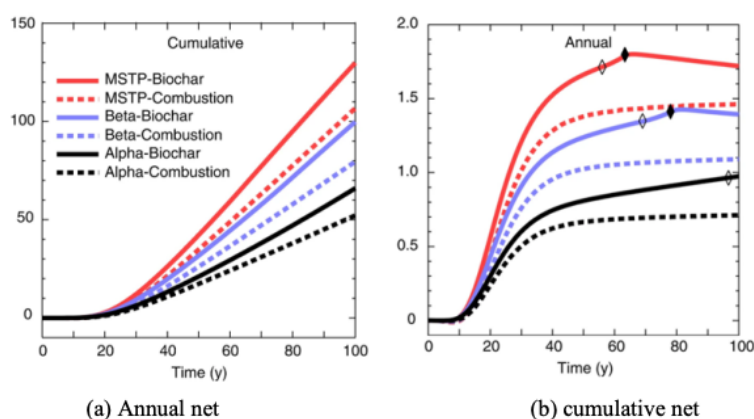


Figure 2. Annual (a) and cumulative (b) net avoided greenhouse gas emissions over 100 years, comparing biochar systems (solid lines) with conventional biomass combustion (dashed lines) [19]

Beyond the clear reductions in CH_4 and N_2O emissions that are now emerging from experimental plots, biochar alters several microbial and biogeochemical soil processes [20]. For croplands applied with fertilizers, biochar can reduce N_2O emissions by up to 48% through the promotion of nosZ-

carrying denitrifying microbe populations that catalyze the final step of converting N_2O into inert dinitrogen [21]. For paddy systems, where the release of CH_4 represents the dominant greenhouse gas signal, similar biochar-induced suppressions of straw-derived CH_4 emissions from around 20% have been reported. Larger meta-analyses confirm such findings in a variety of situations with mean N_2O emission reductions of 38% and overall increases in soil organic carbon and crop yield [22]. Considering these all, microbial alteration, emission suppression, and nutrient retention mechanisms, we should remember that biochar is valuable in agricultural systems beyond being a carbon pool and that we can—and should—use it as a driver of agricultural resilience and productivity.

5.2. Non-agricultural pathways of biochar utilization

Even though agricultural application is still the major application of biochar, there are several non-agricultural applications which are also of considerable value to climate-change mitigation. Waste management is one such potential solution, with the use of biochar made through the decomposition of urban solid waste, forestry residues or agricultural by-products shifting organic waste out of landfills, which effectively removes methane generation and creates a lasting stock of carbon. An example is using coffee grounds that have gone through a biomass conversion process into biochar to partially replace sand in concrete, which raises compressive strength by about 30 percent, lowers cement usage by up to 10 percent and decreases landfill methane emission [22].

A second new application relates to construction material. As a sustainable filler, biochar can be included in cementitious composites, asphalt, and polymer in formulations, improving hydration, mechanical strength and durability and sequestration of carbon in long-lasting infrastructure.

6. Challenges and limitations

The agronomic and environmental advantages of biochar are obvious but the rollout of biochar in large-scale is hindered by a plethora of factors. First of these challenges is the problem of economic viability; life cycle analysis has shown that achieving net negative emissions of biochar requires major initial expenditures in the apparatus to collect the feedstock, transportation, pyrolysis, and field deployment, and the financial reward of such a scheme is relatively minimal, and consists of incremental crop output improvements, or the use of by-products. The cost scheme, shown in negative emissions through biochar (Figure 3) often does not consider any direct sources of revenue, thus highlighting the economic impediment of the mass application of the technique [23].

Another weakness is maturity of the supply chain and the existence of biochar bottlenecks. The industry does not have a consistent distribution system and does not have good market penetration, which is quite different to the well-established fertilizers industries. As a result, the cost of transporting biochar is pushed up and the distribution of biochar is uneven in different regions, which presents great disadvantages to smallholder farms and the remote areas where infrastructure is a constraining factor.

Another dimension of uncertainty regarding the feasibility in the region exists. Economic modelling for temperate regions, including Finland, has demonstrated that biochar can be cost effective in favorable policy contexts, or as part of a carbon credit scheme; but in most tropical or resource-limited situations profitability is impossible without external incentives. These results highlight the need to link biochar promotion to appropriate policy support, subsidies and carbon market inclusion.

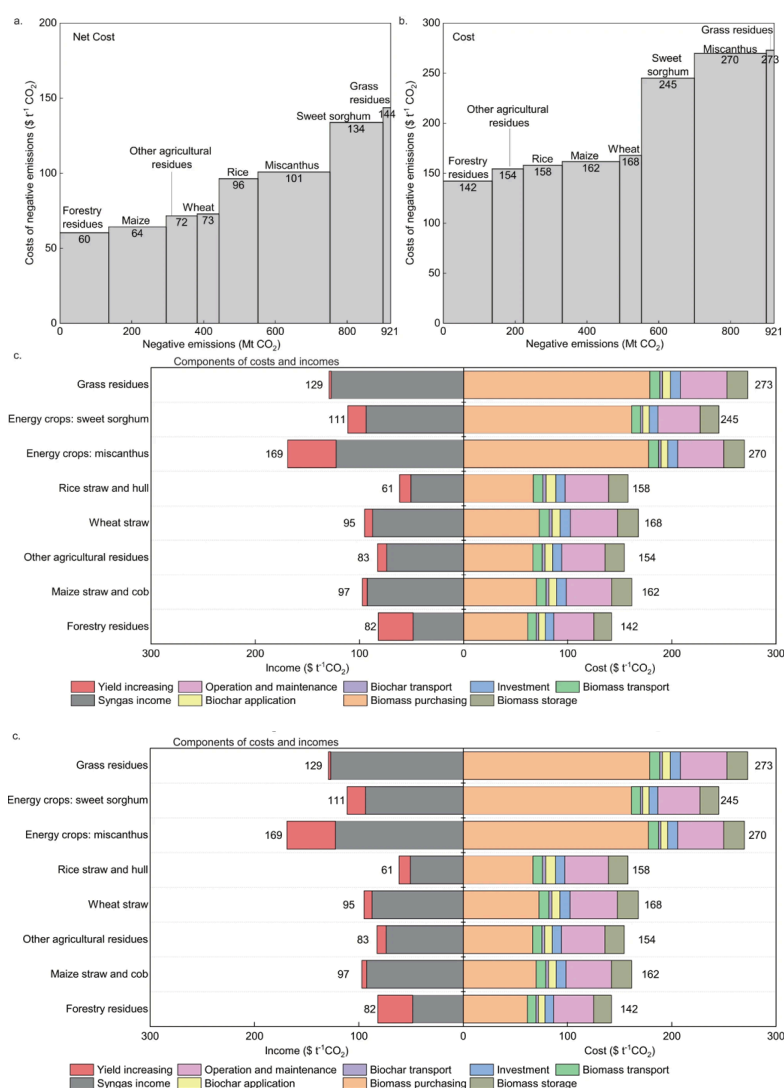


Figure 3. Economic aspects of large-scale biochar implementation: (a) Estimated production costs for different feedstocks and pyrolysis methods; (b) GHG mitigation potential per unit cost, in comparison with other carbon-reducing technologies; (c) Cost and revenue breakdown in large biochar projects, emphasizing the impact of policies and carbon markets on profitability [23]

7. Conclusion

Biochar is a new negative emissions technology with environmental benefits. As a main function, in agriculture, carbon is sequestered in the soil in high amounts, enhances soil fertility and productivity and reduces the emission of other greenhouse gases such as CH₄ and N₂O. Additionally, novel and creative uses in the field of waste management and construction show that biochar can play a similar role in other branches of the circular economy.

Yet, there are still uncertainties concerning the diversity of the biochar feedstock, pyrolysis conditions, soil climate interactions and economic and policy barriers towards large scale deployment that need to be addressed. These can be solved by formulating uniform rules for production, setting up long-term field trials and developing strong governance systems. In total, biochar can play a role in reducing climate change in both the short and long term by incorporation in the carbon sequestration measures and in the management of the resources.

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