Biochar: Improving Soil Health For Sustainable Agriculture

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Abstract:

Biochar, a carbon-rich material derived from biomass pyrolysis, demonstrates strong potential as a multifunctional soil amendment for advancing sustainable agriculture and climate resilience. Based on the reviewed experimental findings and life cycle assessment studies, biochar consistently enhances soil organic carbon, microbial activity, nutrient retention, and water-holding capacity, leading to improved crop productivity and drought tolerance. Its capacity for long-term carbon sequestration and mitigation of methane and nitrous oxide emissions highlights its relevance for climate-smart farming systems. Future research should focus on long-term field trials, optimisation of biochar production parameters, and standardised application strategies across different cropping systems. Addressing economic feasibility and policy support mechanisms will be crucial for large-scale adoption. Overall, biochar holds significant promise as a sustainable tool for soil restoration, climate mitigation, and resilient food production.

1. Introduction of Biochar

Pyrolysis, the scientific term for the thermochemical breakdown of organic biomass in oxygen-limited or oxygen-free circumstances, produces biochar, a stable, carbon-rich, porous solid substance. In contrast to regular charcoal, which is made only for fire, biochar is specifically designed to be applied to soil or larger environmental systems with the main objectives of enhancing soil health, storing carbon, and reducing pollution. Its distinctive feature is its extremely aromatic and resistant carbon structure, which gives it remarkable resistance to chemical weathering and microbial degradation and enables it to endure in soils for centuries to millennia (Lehmann et al., 2021; Murtaza et al., 2023).

From a physicochemical standpoint, biochar is distinguished by a high degree of carbon aromaticity, a large specific surface area, a well-developed porous architecture, and an abundance of functional groups on its surface. Its effectiveness as a soil amendment, carbon sink, and sorbent material for pollutants such as heavy metals, organic contaminants, and excess nutrients is determined by these structural characteristics taken together (Chen et al., 2022; Gao et al., 2023). The choice of feedstock and the parameters of thermal conversion, specifically the pyrolysis temperature, heating rate, and residence time, directly influence the properties of biochar, which researchers are increasingly realising is a spectrum of products rather than a single homogeneous material (Ippolito et al., 2020; Liu et al., 2022).

Biochar has gained a lot of international attention as a negative emission technology in relation to climate change. A significant amount of the carbon that plants acquired from the atmosphere during their growth is successfully trapped in a stable solid state when biomass is turned into biochar instead of being burned openly or allowed to naturally degrade. This technique contributes to net negative greenhouse gas emissions by removing carbon dioxide from the active carbon cycle and moving it into long-term geological storage (Lehmann et al., 2021; Zhu et al., 2022). Biochar systems are one of several promising carbon dioxide removal techniques with great global scaling potential, according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2022).

Beyond its ability to sequester carbon, biochar is a multipurpose material used in the industrial, agricultural, and environmental sectors. In agriculture, it increases soil water retention, improves aeration and porosity, raises the pH of acidic soils, encourages the activity of beneficial soil microbes, and decreases nutrient leaching, all of which lead to increased crop yield (Murtaza et al., 2023; Mašek et al., 2023). It may adsorb and immobilize a variety of hazardous chemicals, such as cadmium, lead, arsenic, and developing organic micropollutants, including antibiotics and pesticides, thanks to its porous structure and chemically reactive surface in environmental remediation (Chen et al., 2022; Tan et al., 2023).

2. Feedstocks used for Biochar

One of the most alluring aspects of this technology is the variety of raw materials that can be used as feedstocks for biochar. According to Ippolito et al. (2020) and Gao et al. (2023), biochar can theoretically be made from any organic biological material, also known as biomass. However, the physicochemical characteristics of the final biochar differ significantly based on the type and composition of the initial material. Generally speaking, feedstocks fall into one of the following main categories:

2.1 Crop Residues from Agriculture

The most accessible and most researched type of biochar feedstock in the world is agricultural residue. Materials such as rice husk, wheat straw, corn stover, sugarcane bagasse, soybean straw, and cotton stalks are generated in enormous quantities as byproducts of food production and are often either openly burned or left to decompose in fields both of which generate greenhouse gas emissions. In addition to preventing these emissions, turning these leftovers into biochar creates a useful soil supplement. For example, wheat straw biochar has been demonstrated to enhance soil organic carbon and nitrogen retention, whereas rice husk biochar stands out for its high silica content and resilience to degradation (Shakoor et al., 2021; Wang et al., 2022; Raza et al., 2023).

2.2 Forest residues and woody biomass

The best biochar feedstocks are those generated from wood, such as hardwood, softwood, sawdust, wood chips, bark, logging leftovers, and timber industry waste. Pyrolysis produces biochar with a high carbon content, highly organised graphitic microstructures, large specific surface areas, and well-developed micro- and mesopore systems because woody materials include a lot of lignin. Because of these qualities, biochars made from wood are very good at storing carbon for a long time and removing pollutants from soil and water. Wood biochar consistently performs better than other feedstocks in terms of carbon stability and surface area development, according to a number of research published between 2022 and 2024 (Liu et al., 2022; He et al., 2023; Aller et al., 2023).

2.3 Poultry litter and animal manures

The pyrolysis of the massive amounts of manure produced by livestock and poultry production into biochar has the combined advantages of resource recovery and waste management. Compared to plant-derived biochars, manure-derived biochars from swine, dairy cattle, and poultry are significantly enriched in nitrogen, phosphorus, potassium, and calcium, offering them great potential as slow-release biofertilizers. To guarantee complete sanitisation and safe end products, it is necessary to carefully control the pyrolysis temperatures because animal manures may also contain heavy metals like copper and zinc from veterinary feed additives, as well as leftover antibiotics and pathogens (Ye et al., 2020; Zhu et al., 2022; Cai et al., 2023).

2.4 Municipal Biosolids and Sludge from Sewage

As cities become more populated, the amount of sewage sludge produced by wastewater treatment facilities worldwide has increased significantly, necessitating the development of sustainable disposal and value-adding methods. Sewage sludge pyrolysis has become a viable method for producing biochar, a mineral-rich substance with a high phosphorus content that can improve soil fertility. Biochars made from sludge have shown the ability to adsorb pharmaceutical chemicals from water and immobilise heavy metals in contaminated soils. However, there are still issues with micropollutants, heavy metals, and polycyclic aromatic hydrocarbons in the raw sludge, necessitating strict optimization of the pyrolysis conditions and post-production quality testing prior to field application (Li et al., 2023; Mian et al., 2022; Fan et al., 2023).

2.5 Agro-industrial Waste and Food Processing

Numerous organic byproducts produced by the food processing industry are underutilised sources of feedstock for biochar. As antecedents to biochar, olive pomace, grape marc, fruit peels, coffee grinds, tea trash, coconut shells, and nut shells have all been studied. The conversion of these materials into biochar adds value to materials that would otherwise burden landfill systems, and they are usually rich in cellulose, hemicellulose, and lignin. Heavy metals and organic dyes can be effectively adsorbed from aqueous systems using biochar made from fruit and vegetable processing wastes (Bolan et al., 2022; Raza et al., 2023; Kumar et al., 2023).

2.6 Biomass from algae

Due to their exceptional growth rates, capacity to be grown on marginal or damaged land using wastewater as a growth medium, and independence from competition from food crops, algae both microalgae and macroalgae, have drawn increasing attention as feedstocks for biochar. Compared to terrestrial plant-based biochars, algal biochar is notably nitrogen-rich and exhibits a special surface chemistry that makes it an excellent adsorbent of phosphate, ammonia, and heavy metal ions. In comparison to many conventional feedstocks, algae-derived biochars perform better at simultaneous nutrient recovery and contaminant immobilisation, according to a thorough review by Wang et al. (2023). This makes algal biochar an especially sustainable choice for circular bioeconomy applications.

2.7 Dedicated Bioenergy Plants and Energy Crops

Miscanthus, switchgrass, bamboo, giant reed, and willow are examples of perennial energy crops that are grown especially for the co-production of bioenergy and biochar. These plants stand out for their high biomass productivity, quick development on marginal or contaminated soils, and low need for pesticides and fertilisers. These energy crops are used to make biochar, which typically has a high carbon content and good structural stability. Energy crop biochar systems can provide true greenhouse gas removal because the total carbon balance is strongly negative due to the active removal of carbon from the atmosphere during the growth phase and the subsequent pyrolysis that locks the carbon into stable biochar (Mašek et al., 2023; He et al., 2023).

3. Conditions of Pyrolysis and How They Affect the Quality of Biochar

The temperature at which pyrolysis is carried out has a significant impact on the properties of biochar. A higher percentage of labile organic compounds is often retained in low-temperature biochars (300–450 °C), resulting in products with higher cation exchange capacity, higher nutritional content, and more functional surface groups, but correspondingly poorer carbon stability and surface area. The reverse profile is seen in high-temperature biochars (550–700 °C), which have less surface reactivity and nutrient load but more aromaticity, surface area, and structural stability (Zhao et al., 2022; Chen et al., 2023). These correlations are further modulated in ways that are still being mapped in the literature by the reactor's residency duration, heating rate, and ambient conditions.

Alternative thermochemical processes that go beyond traditional slow pyrolysis have garnered more and more study interest. Gasification, hydrothermal carbonisation (HTC), and flash carbonization all result in carbon-rich materials with different characteristics from those of conventionally pyrolysed biochar (Fang et al., 2022). Despite having a generally lower degree of aromatization, HTC in particular has been highlighted as a promising method for processing wet feedstocks, such as sewage sludge and animal manures, without the energy-intensive drying step needed for conventional pyrolysis. The resulting hydrochar exhibits intriguing soil conditioning properties (He et al., 2023). The planned use and the available feedstock must therefore be taken into consideration when selecting the manufacturing pathway.

4. BIOCHAR'S IMPACT ON THE PHYSICAL PROPERTIES OF SOIL

4.1 Soil Bulk Density and Structure

Because of significant mechanical compaction and the loss of organic content that would otherwise preserve aggregate stability, degraded agricultural soils often have high bulk densities. By physically occupying interaggregate space, encouraging the formation of stable macroaggregates, and providing organic carbon that feeds the microbial communities in charge of binding soil particles into structurally sound units, the application of biochar has been shown to reduce soil bulk density, especially in fine-textured soils (Sun et al., 2022).

Biochar application at rates above 20 Mg ha^{-1} reduced bulk density by a weighted mean of 7.4%, according to a meta-analysis of 174 field and greenhouse studies published by Li et al. (2023). The largest reductions were seen in sandy soils and in studies using biochar produced at high pyrolysis temperatures. However, the authors pointed out that the effects varied and that in soils with low bulk density, very high application rates occasionally produced neutral or slightly negative results.

It has also been noted that adding biochar improves aggregate stability, a gauge of how well soil structure units withstand disturbance from rainfall and ploughing. In a two-year field trial, Dong et al. (2023) examined the effects of wheat straw biochar on aggregate stability in a degraded silty loam and found significant increases in the mean weight diameter of water-stable aggregates. They attributed the improvement to both the indirect stimulation of fungal hyphal networks that bind aggregates and the direct physical role of biochar fragments in anchoring microaggregates. These results are consistent with more extensive evidence that the microbial community alterations brought about by biochar have long-term effects on the physical characteristics of soil that go far beyond the direct physical presence of the amendment.

4.2 Hydraulic Conductivity and Water Retention

The ability of biochar to enhance soil water retention, especially in sandy, coarse-textured soils that are prone to quick drainage, is arguably the most well-documented physical advantage. The network of mesopores and micropores created by the porous interior structure of biochar particles can retain significant amounts of water against gravitational drainage while releasing it to plant roots at tensions that fall within the physiologically accessible range (Novak et al., 2022). Biochar increased plant-available water content by an average of 11% across all soil types studied, according to a thorough review by Razzaghi et al. (2023). The effects were most noticeable and agriculturally significant in soils with initial clay contents below 15%.

The situation is more complicated in soils that contain a lot of clay. According to a number of recent studies, biochar can either improve drainage in poorly structured, wet soils by breaking up dense clay layers and creating preferential flow pathways, or it can decrease water retention in already high-retention soils by upsetting the existing microstructure (Zhang et al., 2022; Omondi et al., 2023). As a result, the hydraulic conductivity response to biochar seems to be very soil-specific, highlighting the necessity of site-specific application techniques rather than general guidelines.

Improvements in water retention have immediate economic effects from the standpoint of agricultural management since they lower the need for irrigation. Even slight increases in soil water-holding capacity can result in significant yield increases and a lower risk of crop failure in water-stressed areas of sub-Saharan Africa, South Asia, and portions of Latin America, where smallholder farmers deal with ongoing drought stress and lack access to additional irrigation (Mwanza et al., 2023). Growing policy interest in biochar adoption within international frameworks addressing both food security and climate adaptation has been fueled by this aspect of biochar's potential.

5. BIOCHAR'S IMPACT ON THE CHEMICAL PROPERTIES OF SOIL

5.1 pH of Soil and the Impact of Liming

Many degraded agricultural soils suffer from acidification brought on by decades of ammonium-based fertilizer use and base cation leaching. Soil pH is a master variable that controls the availability of almost all plant-essential nutrients as well as the solubility of potentially toxic elements. Because it contains carbonates, bicarbonates, and basic oxide ash, biochar is usually alkaline in reaction. It has been used extensively as a liming agent in acidic soils, and many studies have confirmed that it can raise pH and improve the availability of phosphorus, calcium, magnesium, and molybdenum while lowering the phytotoxic availability of aluminium and manganese (Ippolito et al., 2020; Meng et al., 2022).

The goal of recent research has been to better understand the lifetime of biochar and to measure its pH-buffering impact. Prado et al. (2023) conducted a controlled incubation study that tracked the pH trajectories of two tropical Oxisols amended with rice husk biochar over a 24-month period. They discovered that while the initial pH increase was significant (mean 0.8 pH units), the effect gradually decreased as the biochar's more soluble alkaline components leached or reacted with soil acids. Crucially, though, the longer-term residual effect was still statistically significant at month 24, indicating that the liming action of biochar persists beyond a single growing season even though it is not permanent. When pH control is the main goal, the scientists suggested that periodic low-rate administrations would be more agronomically effective than single large doses.

5.2 Capacity for Cation Exchange and Retention of Nutrients

One of the main factors determining a soil's intrinsic fertility and resistance to nutrient leaching is its cation exchange capacity (CEC), or its capability to retain and exchange positively charged nutrient ions. By directly adding negatively charged surface functional groups (mainly carboxylic and phenolic groups) and by promoting the breakdown of native soil organic matter, which in turn creates exchange sites, biochar can improve CEC through two main mechanisms (Mukherjee et al., 2023). Low-temperature biochars have the most contribution from direct surface functional groups, and this contribution grows over time as the biochar surface oxidizes after soil incorporation, a process known as "ageing" of the biochar (Liu et al., 2022).

Recent years have seen the publication of several long-term field studies that offer important real-world information on the temporal dynamics of biochar-mediated CEC alterations. In a study conducted nine years following a single application of spruce-wood biochar in a boreal agricultural soil, Tammeorg et al. (2022) discovered consistent, statistically significant increases in CEC in comparison to unaltered control plots. In a similar vein, Yang et al.'s (2023) ten-year study in a subtropical paddy soil verified long-term gains in ammonium, calcium, and magnesium retention in biochar-amended plots, which correlated with quantifiable decreases in nutrient loss to drainage waters. Because they go beyond the brief observational windows that define a large portion of the current literature, these multi-year datasets are very significant.

5.3 Dynamics of Phosphorus

One of the most technically challenging aspects of soil fertility is managing phosphorus because it is both necessary for plant growth and prone to fixation in forms that roots cannot access, especially in acidic soils with high iron and aluminum content and alkaline soils with high calcium levels. As a result, the impact of biochar on phosphorus availability is complicated and difficult to generalise. Biochar application has been shown to increase available phosphorus at slightly acidic to neutral pH values by releasing organic phosphorus compounds from the biochar itself, reducing sorption to iron and aluminium oxides as pH rises, and promoting microbial mineralization of organic phosphorus (Backer et al., 2022; Xu et al., 2023).

However, even though the overall pool is increased, there is a chance that phosphorus will re-fix as calcium phosphates at higher application rates or when alkaline biochars are added to soils that are already neutral. This would decrease plant availability. According to research by Gao et al. (2023), rice straw biochar at 40 Mg ha^{-1} actually decreased Olsen-P availability in calcareous soils in northern China when compared to lesser application rates. This was mainly due to the precipitation of dicalcium phosphate at the increased pH created by the amendment. These subtleties emphasise how crucial it is to take local soil chemistry into account when developing biochar application tactics meant to overcome phosphorus restrictions.

5.4 Immobilisation of Heavy Metals

The ability of biochar to immobilize potentially hazardous trace metals in contaminated agricultural soils, hence lowering crop uptake and human exposure through the food chain, is one of the most quickly growing fields of biochar study. Millions of hectares of agricultural land globally are affected by heavy metal contamination from mining, industrial effluent, atmospheric deposition, and the long-term application of sewage sludge; therefore, there is an urgent need for affordable in-situ remediation technology (Bolan et al., 2022). Electrostatic attraction to negatively charged surface sites, precipitation as metal hydroxides or carbonates at the elevated pH produced by alkaline biochars, co-precipitation with phosphate minerals, and complexation with surface organic functional groups are some of the ways that biochar immobilizes metals (Ahmad et al., 2022).

The application of biochar decreased plant-available lead concentrations in contaminated soils by a mean of 38%, cadmium by 42%, arsenic by 29%, and chromium by 34%, according to a meta-analysis by Zhao et al. (2023) that synthesized data from 89 pot and field experiments. The effectiveness varied systematically with pyrolysis temperature, application rate, and initial contamination level. Although they were more expensive to produce, engineered biochars those altered after production with substances like magnesium oxide, iron salts, or chitosan to improve particular sorption qualities consistently performed better in metal immobilization than unmodified biochars (Hou et al., 2023). An important topic of continuing research is whether immobilized metals could be remobilized under conditions of soil acidity or microbially induced redox shift.

6. BIOCHAR'S IMPACT ON THE BIOLOGICAL PROPERTIES OF SOIL

6.1 Structure and Diversity of Soil Microbial Communities

Almost all of the biochemical changes that support soil fertility and ecosystem function are driven by the living component of soil, which is its microbial community, which includes bacteria, fungi, archaea, and their related viral groups. Therefore, changes in this community have profound effects on plant health, disease suppression, organic matter breakdown, and nutrient cycling. Although the direction and strength of these impacts are very dependent on the characteristics of the biochar and the soil context, it has been repeatedly demonstrated that biochar can change the number and community composition of soil microorganisms (Lehmann et al., 2022).

Increases in total microbial biomass, changes in the composition of bacterial communities toward taxa linked to organic carbon breakdown and nutrient cycling, and frequently increases in fungal abundance and hyphal density are the most commonly documented microbiological reactions to biochar. Because fungal hyphae are essential to the development of soil aggregates and the breakdown of stubborn organic molecules, the latter discovery has garnered special attention. Biochar consistently increases the relative abundance of Actinobacteria, Firmicutes, and some fungal phyla, such as Ascomycota and Basidiomycota, while decreasing the proportion of taxa associated with anaerobic or compaction-stressed conditions, according to high-throughput amplicon sequencing studies published between 2022 and 2024 (Zhang et al., 2023; Chen et al., 2024).

The increasing use of metagenomic and metatranscriptomic techniques to characterize the functional potential of biochar-modified microbial communities, going beyond taxonomic description to comprehend what those communities actually do, has been a particularly exciting development in recent literature. In a three-year field trial, Luo et al. (2023) used shotgun metagenomics on soils and discovered that biochar-amended plots harbored communities with significantly enriched functional gene repertoires related to phosphorus mineralization, nitrogen fixation, and the degradation of complex polysaccharides. This finding provided a mechanistic basis for observed improvements in nutrient availability that could not have been revealed by simple taxonomic profiling.

6.2 Mycorrhizal Relationships

From an agricultural standpoint, arbuscular mycorrhizal fungi (AMF) are among the most ecologically relevant families of soil organisms because they create symbiotic relationships with the great majority of crop species. In addition to providing advantages in terms of drought tolerance, disease resistance, and soil aggregate formation, AMF enhances plant access to immobile nutrients, especially phosphorus and zinc, by extending the effective root system of host plants into soil volumes beyond the phosphorus depletion zone. Numerous studies have shown that biochar increases AMF colonization of crop roots, mainly by enhancing soil pore architecture, lowering heavy metal stress that would otherwise inhibit AMF activity, and possibly releasing stimulatory compounds during initial weathering (Jaafar et al., 2022).

In a controlled greenhouse experiment, Qin et al. (2023) found that maize plants growing in sandy soils amended with biochar had 23% higher AMF root colonization rates than unamended controls. This resulted in considerably higher shoot dry weight and phosphate uptake efficiency. Increased availability of myo-inositol compounds, which act as signaling molecules in the early phases of symbiosis establishment, and enhanced soil pore connectivity, which promotes hyphal growth, both seemed to be part of the mechanism. The reduction of phosphorus fertilizer inputs in sustainable farming systems is closely related to these findings.

6.3 Nutrient Cycling and Enzyme Activities

A comprehensive indicator of the microbial community's biochemical activity, soil enzymatic activity is intimately related to the rates of nutrient cycling that determine the amount of nutrients accessible to crops. The most commonly measured indicators in biochar studies have been dehydrogenase, urease, phosphatase, and β-glucosidase activities. A consistent pattern appears in the literature from 2022 to 2026: the application of biochar tends to increase the activities of these enzymes, with the magnitude of response depending on the quality and quantity of biochar applied (Wang et al., 2022; Meng et al., 2023).

Enzyme stimulation is caused by a variety of methods. By adsorbing extracellular enzymes onto mineral-like surfaces while maintaining catalytic activity, biochar surfaces may shield them from proteolytic destruction. Enzyme synthesis is directly increased by increased microbial biomass after the addition of biochar. Furthermore, improvements in soil structure and aeration brought about by biochar may lessen anaerobic microsites, which would otherwise prevent the functioning of aerobic heterotrophic bacteria that produce important enzymes. In order to separate the direct enzyme-protective effect from the indirect microbial stimulation effects, Bhattacharya et al. (2023) deftly separated these pathways using sterilized biochar treatments. They discovered that both pathways functioned concurrently and contributed about equally to the observed activity increases.

7. GREENHOUSE GAS EMISSIONS FROM SOIL AND BIOCHAR

About 10–12% of the world's anthropogenic greenhouse gas emissions come from agriculture, and soils are important sources of both methane (CH_4), which is mostly released from anaerobic environments like flooded rice paddies and ruminant digestive systems, and nitrous oxide (N_2O), a powerful greenhouse gas mainly produced through microbial nitrification and denitrification. Due to its potential for direct climate mitigation as well as its synergy with carbon sequestration through stable organic carbon incorporation into soil, biochar's ability to alter both of these emission pathways has garnered significant study interest.

In general, the data on N2O is positive. Biochar application decreased soil N2O emissions by a weighted mean of 25% under all conditions, according to a meta-analysis by Song et al. (2023) that included 146 independent studies. The biggest reductions, up to 54%, were seen in soils with high nitrogen inputs, high moisture content, and neutral to slightly acidic pH. In addition to the sorption of ammonium and nitrate onto biochar surfaces, which decreases the substrate available for denitrifying bacteria, the main process seems to entail biochar's improvement of soil aeration and reduction of anaerobic microsites that encourage denitrification. A biological mechanism of particular relevance has been shown in a number of recent studies: further suppression by activation of N2O-reducing bacteria expressing the nosZ gene (Senbayram et al., 2022).

For CH_4 emissions, the situation is more complex and situation-specific. Biochar typically lowers CH_4 emissions in paddy rice systems, where anaerobic conditions during flooding encourage methanogenic archaea activity. This is said to happen by enhancing soil redox status, stimulating competing electron acceptors, and encouraging methanotrophic bacteria that eat CH_4 before it enters the atmosphere (Fang et al., 2023). The concurrent impact on N2O must be taken into account, though, since drainage upgrades that lower CH_4 can occasionally raise N2O, somewhat counteracting the climate advantage. Therefore, in order to appropriately characterize net climate effects, integrated whole-season greenhouse gas budgets stated in CO2-equivalent terms are crucial, and these comprehensive assessments are still underrepresented in the literature.

In terms of carbon sequestration, the stable aromatic carbon in biochar is a real addition to long-term soil organic carbon stocks that won't be quickly released back into the atmosphere by microbial metabolism like traditional organic additions would. According to modeling studies by Woolf et al. (2022), applying biochar on a global scale to degraded agricultural soils using sustainably sourced feedstocks could sequester between 1 and 1.8 Pg CO2-equivalent annually. When combined with other strategies, this could be a significant part of climate mitigation portfolios. The scientists emphasized, however, that these numbers are predicated on industrial systems achieving high energy efficiency and careful feedstock sourcing that prevents emissions from land-use change.

8. CROP PRODUCTIVITY AND BIOCHAR

The ability of biochar to support or improve crop yields in ways that farmers find economically significant ultimately determines its acceptance in agricultural systems. The soil, climate, and agricultural system in question all play a role in the complicated and nonlinear relationship between biochar application and crop productivity. Average yield gains of roughly 10–15% across a variety of agricultural systems were reported in early meta-analyses released before to 2020, while there was significant variation between research. This order of magnitude has generally been validated by more recent investigations, which also shed more light on the factors that influence whether responses are positive, neutral, or occasionally negative.

In a comprehensive meta-analysis of 2,489 paired observations from 423 published studies, Dai et al. (2023) discovered a mean increase in crop yield of 14.2% after applying biochar. The study found that soil pH (strongest responses in acid soils), soil texture (strongest effects in sandy soils), biochar application rate (an optimum at about 20–30 Mg ha^{-1} beyond which incremental benefits diminished), and biochar feedstock (manure-derived biochars tend to produce larger yield gains than wood-derived biochars, probably due to higher nutrient contributions). Tropical systems generally benefited more than temperate ones, and cereals responded more consistently than legumes or root crops.

The persistence of yield gains across several growing seasons after a single application of biochar is a crucial practical challenge. Here, long-term field experiment data have proven useful. The biggest yield responses happened in the first two to three years after application, according to research by Jeffrey et al. (2022) that reviewed trials lasting five or more years. As the more reactive biochar components aged and its main contribution shifted from nutrient supply to longer-term structural benefits, subsequent years showed smaller but still positive effects. Economic analysis and the creation of soil amendment plans that include biochar with other inputs like compost or mineral fertilizers are also impacted by these temporal dynamics.

Several recent studies have shown synergistic interactions between biochar and traditional mineral fertilizers, indicating that biochar may increase fertilizer usage efficiency by lowering nutrient losses through leaching and volatilization (Ding et al., 2023). Practically speaking, this means that biochar-amended soils may produce comparable results with less fertilizer inputs, lowering production costs and the environmental externalities related to the production and application of fertilizers. Wang et al. (2024) found that biochar amendment permitted a 20% reduction in nitrogen fertilizer rate without impacting yield in trials carried out in China's intensive vegetable production systems. This was mainly due to decreased ammonia volatilization and nitrate leaching from treated soils.

9. IMPORTANT LIMITS AND FUTURE RESEARCH DIRECTIONS

Even though this study shows significant progress, there are still a number of important issues that need to be resolved before biochar can reach its full potential as a widely used technique for sustainable soil management. The requirement for more uniformity and standardization in experimental design and reporting is the first of these. The current literature is characterized by significant heterogeneity in biochar characterization techniques, application rates, experimental duration, and measured outcome variables, as noted in several recent meta-analyses. This makes cross-study comparisons challenging and limits the accuracy of pooled effect size estimates (Bai et al., 2023). Standardized biochar characterization procedures, such those put out by the European Biochar Certificate and the International Biochar Initiative, are a significant advance, but publishing researchers still need to embrace them more widely.

One recurrent and significant issue is the discrepancy between short-term laboratory outcomes and long-term field performance. While the soil processes under study take years or decades to develop, most published research on the impacts of biochar on soil biology, enzyme activity, and nutrient cycling is done during weeks to months. To give the temporal perspective needed to direct useful management suggestions, multi-year, multi-site field trials with robust experimental designs are desperately needed. Progress in this area would be significantly accelerated by the creation of global networks of biochar field trial sites that exchange data and standards.

For standard production conditions and feedstocks, the safety of biochar as a soil input is generally well established; however, concerns about the possible accumulation of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other contaminants in biochars made from specific feedstocks, such as sewage sludge or mixed municipal organic waste, still exist (Freddo et al., 2022). Many jurisdictions are still creating regulatory frameworks for biochar quality assurance, and maintaining vigilance and strong quality control systems will be necessary to guarantee farmer and customer confidence in product safety.

Lastly, studies on how biochar interacts with new agricultural techniques, such as cover crops, agroforestry, precision farming, digital soil mapping, and regenerative agriculture systems, are still in their infancy. Realizing biochar's full complimentary potential will require an understanding of how it functions within these interconnected systems rather than in isolation. It will require interdisciplinary cooperation between soil scientists, agronomists, ecologists, economics, and social scientists to convert experimental findings into practically feasible, socially acceptable, and contextually appropriate soil health initiatives.

10.CONCLUSION

In the context of sustainable agriculture, the information compiled in this study makes it clear that biochar is a truly useful and adaptable tool for enhancing soil health. Biochar provides a range of functions that no single conventional amendment can match by simultaneously addressing several aspects of soil quality through its effects on soil physical structure, water retention, pH, nutrient availability, microbial community composition, enzyme activity, and greenhouse gas dynamics. Between 2022 and 2026, research has significantly expanded our understanding of the mechanisms underlying these effects, shifted the evidence base from lab and pot experiments to multi-year field trials, and started to seriously consider the practical and economic aspects of large-scale biochar deployment.

However, this review also demonstrates that biochar is not a panacea. Its efficacy varies greatly depending on the feedstock, production conditions, soil type, climate, and management method. Regulatory frameworks for quality assurance are still developing, and high costs continue to be a major obstacle to wider use. It will take sustained investment in long-term field research, standardized reporting, policy frameworks that acknowledge and reward soil carbon and environmental service contributions, and extension programs that assist farmers in making site-specific, well-informed decisions in order to fully realize the potential of biochar.

In the end, humanity's problems with soil health are too serious and complicated to be solved by a single intervention. It is best to view biochar as a potent part of a more comprehensive, integrated approach to sustainable soil management, which integrates physical, chemical, and biological techniques with good agronomic practice, mindful land stewardship, and an unwavering dedication to preserving the soil resource that underpins all terrestrial food production.

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