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Mukesh R

Assistant Professor (Soil Science and Agricultural Chemistry), MIT College of Agriculture and Technology, Musiri, Tiruchirapalli, Tamil Nadu, India

Preethi KD

Assistant Professor (Soil Science and Agricultural Chemistry), MIT College of Agriculture and Technology, Musiri, Trichy, Tamil Nadu, India

Ashok Kumar M

Assistant Professor (Soil Science and Agricultural Chemistry), GPS Institute of Agricultural Management, Bengaluru, Karnataka, India

Biochar in soil systems: Effects on soil properties, nutrient dynamics and crop performance

Mukesh R, Preethi KD and Ashok Kumar M

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Abstract

Biochar, a carbon-rich material produced by pyrolysis of organic feedstocks under limited or absent oxygen conditions, has emerged as a promising soil amendment with multifaceted benefits for agriculture and the environment. This review comprehensively examines the effects of biochar on soil physical, chemical and biological properties, nutrient dynamics and crop performance based on evidence from global field trials, pot experiments and laboratory studies. Biochar application has been consistently shown to improve soil bulk density, porosity, water-holding capacity and aggregate stability. Chemically, it enhances soil pH in acidic soils, elevates cation exchange capacity (CEC), increases soil organic carbon (SOC) content and improves nutrient retention and availability. The porous structure of biochar provides a favorable microhabitat for soil microorganisms, thereby enhancing microbial biomass, diversity and enzymatic activity, which are essential for nutrient cycling. Biochar reduces the leaching of nitrogen and other macro/micronutrients, improves fertilizer use efficiency and contributes to long-term carbon sequestration. In terms of crop performance, biochar amendments have demonstrated positive effects on plant growth, root architecture, biomass accumulation and grain yield across a wide range of crops and soil types. However, the magnitude of these benefits is highly dependent on feedstock type, pyrolysis temperature, application rate, soil characteristics and climatic conditions. This review also highlights existing research gaps, particularly the need for standardized protocols, long-term field studies across diverse agro-climatic zones and economic feasibility assessments for large-scale adoption.

Keywords: Biochar, soil amendment, nutrient dynamics, crop performance, carbon sequestration, soil microbiology

1. Introduction

Soil degradation, declining organic matter and reduced agricultural productivity are among the most pressing challenges facing modern agriculture, particularly in tropical and subtropical regions. The depletion of soil organic carbon (SOC), excessive use of synthetic fertilizers and intensive tillage practices have collectively contributed to the deterioration of soil health and long-term fertility. In this context, biochar - a stable, carbon-rich solid produced through the thermochemical decomposition of organic materials (biomass) in the absence or limited presence of oxygen - has attracted considerable scientific attention as a sustainable soil amendment [44, 68].

The concept of biochar is not new; its origins can be traced to the ancient Amazonian practice of creating "terra preta" (dark earth), where pre-Columbian civilizations improved infertile soils using charcoal and organic residues, producing soils that remain highly fertile to this day [27]. Modern biochar research has expanded dramatically since the early 2000s, driven by interests in climate change mitigation, waste management and sustainable agricultural intensification [69, 76]. Biochar is produced from a wide range of feedstocks including crop residues (rice straw, wheat straw, sugarcane bagasse), woody biomass, animal manures, sewage sludge and municipal solid waste, through processes such as slow pyrolysis, fast pyrolysis, gasification and hydrothermal carbonization [12]. The physical and chemical properties of the resulting biochar - including its surface area, porosity, pH, nutrient content and stability - are profoundly influenced by the feedstock composition and the pyrolysis conditions, particularly temperature [17].

Research has demonstrated that biochar influences soil properties through multiple mechanisms: it alters soil texture and structure, modifies soil pH and CEC, enhances water retention, provides

Corresponding Author:

Mukesh R

Assistant Professor (Soil Science and Agricultural Chemistry), MIT College of Agriculture and Technology, Musiri, Tiruchirapalli, Tamil Nadu, India

labile carbon and nutrients and creates physical habitats for soil microorganisms [4, 9]. These changes collectively influence nutrient availability and cycling, with downstream effects on plant nutrition and productivity. Additionally, the recalcitrant nature of biochar carbon means it persists in soils for centuries to millennia, making biochar application a powerful strategy for long-term carbon sequestration and climate change mitigation [45].

This review synthesizes current knowledge on the effects of biochar on: (i) soil physical properties, (ii) soil chemical properties, (iii) soil biological properties, (iv) nutrient dynamics and (v) crop performance. It further identifies knowledge gaps and future research priorities to facilitate the effective and sustainable use of biochar in global agricultural systems.

2. Biochar: Production, Types and Properties

Biochar is produced through pyrolysis - the thermal decomposition of organic matter in the absence of oxygen. The properties of biochar are primarily determined by feedstock type and pyrolysis temperature. Generally, pyrolysis temperatures above 500 degrees C produce biochar with higher aromaticity, greater surface area and increased stability, while lower temperatures (300-400 degrees C) yield biochars with higher nutrient content and functional groups that are more reactive but less persistent in the soil [80].

Common biochar feedstocks include rice husk, wheat straw, corn cob, sugarcane bagasse, wood chips, dairy manure, poultry litter and sewage sludge. Each feedstock imparts distinct characteristics; for example, manure-derived biochars tend to have higher nitrogen and phosphorus content, while wood-derived biochars exhibit greater porosity and surface area [23, 67].

Key physicochemical properties of biochar include: (i) high surface area (ranging from 1 to over 400 m² g⁻¹), (ii) significant porosity with pore sizes spanning the macro, meso and micro range, (iii) alkaline pH (typically 7-11), (iv) high CEC (5-50 cmol kg⁻¹), (v) carbon content (50-90%) and (vi) variable nitrogen, phosphorus and potassium concentrations depending on feedstock [17, 32]. These properties collectively govern biochar's behavior and functionality when applied to soil.

3. Effects of Biochar on Soil Physical Properties

3.1 Bulk Density and Porosity

One of the most consistently reported effects of biochar application is a reduction in soil bulk density, particularly in heavy-textured soils. The low inherent density of biochar (typically 0.3-0.6 g cm⁻³) combined with its porous structure contributes to the dilution effect and structural improvement of the soil. [55] conducted a meta-analysis of 114 data points from published studies and found that biochar application reduced soil bulk density by an average of 3.4% to 31.4%, with the greatest reductions observed at higher application rates (>20 t ha⁻¹).

Biochar's high internal porosity also significantly increases total soil porosity and enhances the connectivity of pore networks. This improvement facilitates better aeration, gas exchange and root penetration, creating a more favorable rooting environment for crops [51]. In compacted soils common in intensively cultivated tropical regions of India, biochar at 5-10 t ha⁻¹ has been shown to significantly reduce compaction and improve soil tilth [40].

3.2 Water-Holding Capacity and Hydraulic Conductivity

Biochar's porous structure and large surface area play a critical role in improving soil water-holding capacity (WHC). The macro and mesopores of biochar physically retain water and

reduce its rapid loss through drainage, while surface functional groups aid in moisture adsorption. Meta-analyses indicate that biochar application increases WHC by an average of 18-25% across diverse soil types, with sandy soils showing more dramatic improvements than clay soils [11, 63].

The effect of biochar on saturated hydraulic conductivity (Ksat) is more variable and depends on the initial soil texture. In clay-dominated soils, biochar can improve Ksat by alleviating compaction and enhancing macroporosity. In sandy soils, the filling of macropores by biochar particles may slightly reduce Ksat but simultaneously increases available water content, improving drought resilience [25]. These improvements in soil water dynamics are particularly valuable in rainfed agricultural systems where water stress is a major yield-limiting factor.

3.3 Soil Aggregate Stability and Erodibility

Soil structural stability, as measured by aggregate stability, is a key indicator of soil quality. Biochar enhances aggregate formation and stability through several mechanisms: it increases SOC - the primary binding agent for soil aggregates - stimulates microbial activity (which produces exopolysaccharides and glomalin that glue soil particles) and physically acts as a nucleus for aggregate formation [36, 48].

Improved aggregate stability reduces susceptibility to rainfall-induced erosion, enhances water infiltration and reduces surface runoff. Research in degraded tropical soils has demonstrated that biochar application at 10-20 t ha⁻¹ significantly improved mean weight diameter (MWD) of aggregates and reduced soil loss by up to 45% under simulated rainfall conditions [59].

4. Effects of Biochar on Soil Chemical Properties

4.1 Soil pH Modification

The majority of biochars are alkaline in reaction due to the presence of carbonates, bicarbonates, oxides and hydroxides of calcium, magnesium, potassium and sodium on their surface. Application of such biochars to acidic soils results in a liming effect, raising soil pH and alleviating aluminum and manganese toxicity, which are among the primary constraints in acid soil agriculture [20]. A meta-analysis by Biederman and Harpole [10] reported an average increase of 0.53 pH units following biochar application, with greater responses in soils with initial pH < 5.5. In Tamil Nadu and other parts of peninsular India where acidic red laterite soils are common, biochar produced from crop residues has shown promising results in neutralizing soil acidity and improving nutrient availability - particularly phosphorus, which is highly fixed in acidic conditions [53]. However, caution must be exercised in already alkaline soils (pH > 8), as further pH elevation may induce micronutrient deficiencies.

4.2 Cation Exchange Capacity and Nutrient Retention

Cation exchange capacity (CEC) is a measure of the soil's ability to hold positively charged ions (cations) and is a critical determinant of soil fertility. Fresh biochar typically has low CEC, but through oxidation and weathering over time, carboxylic and phenolic functional groups develop on its surface, significantly increasing CEC [16]. Several studies have reported CEC increases of 20-50% following biochar application, with higher responses in low-CEC sandy soils. Enhanced CEC reduces the leaching of essential cations including calcium (Ca²⁺), magnesium (Mg²⁺), potassium (K⁺) and ammonium (NH₄⁺), thereby improving their availability to plants. This is particularly important in tropical soils with inherently low CEC due to low organic matter content and kaolinitic clay mineralogy [42].

4.3 Soil Organic Carbon and Humus Formation

Biochar application directly increases soil organic carbon (SOC) due to the recalcitrant nature of its aromatic carbon skeleton. Unlike other organic amendments such as compost or green manure, biochar carbon resists microbial decomposition and persists in soil for centuries, contributing to stable SOC pools^[81]. Studies have documented SOC increases of 30-300% depending on application rate and initial SOC level. Beyond direct carbon contribution, biochar may also stimulate the formation of native humus by promoting microbial processing of organic matter and physical protection of organic compounds within its pore structure. However, some studies report a “priming effect” where biochar stimulates the decomposition of native SOC, though this effect is generally modest and short-lived^[49].

5. Effects of Biochar on Soil Biological Properties

5.1 Microbial Biomass and Community Structure

Soil microorganisms are the primary drivers of nutrient cycling and organic matter decomposition and their activity is a sensitive indicator of soil health. Biochar creates a favorable habitat for soil microorganisms by providing refugia from predation, adsorbing inhibitory compounds, supplying labile carbon and nutrients and moderating soil moisture and temperature extremes^[71]. Numerous studies have reported significant increases in microbial biomass carbon (MBC) following biochar application, with reported increases ranging from 15% to over 100%^[62]. The effects on microbial community composition are more nuanced. While bacteria and fungi generally respond positively to biochar, the fungal-to-bacterial ratio and the abundance of specific functional guilds (e.g., nitrifiers, denitrifiers, mycorrhizal fungi) vary with biochar type and soil conditions. High-temperature biochars with low volatile content may initially suppress microbial activity, while low-temperature, nutrient-rich biochars stimulate rapid microbial colonization^[15].

5.2 Enzyme Activity and Nutrient Cycling

Soil enzymes, including urease, phosphatase, dehydrogenase and beta-glucosidase, play essential roles in the mineralization of organic nitrogen, phosphorus and carbon. Biochar application has been shown to enhance the activity of these enzymes through increased microbial biomass and by acting as a substrate for enzyme immobilization, protecting them from denaturation^[5, 43].

Enhanced phosphatase activity following biochar application is of particular significance in phosphorus-deficient soils, as it facilitates the mineralization of organic phosphorus to plant-available inorganic forms. Similarly, increased dehydrogenase activity serves as an indicator of improved overall biological metabolism and electron transport in the soil ecosystem^[58].

5.3 Arbuscular Mycorrhizal Fungi (AMF) and Plant Symbiosis

Arbuscular mycorrhizal fungi (AMF) form mutualistic associations with the roots of approximately 80% of terrestrial plant species and play a critical role in phosphorus acquisition, water uptake and pathogen protection. Several studies have reported enhanced AMF colonization and spore density in biochar-amended soils, attributed to biochar's ability to provide a favorable microhabitat, reduce soil phosphorus fixation and alter soil pH toward the optimum for AMF growth^[64, 75]. Enhanced AMF colonization in biochar-amended soils has been linked to improved plant drought tolerance and nutrient uptake,

particularly phosphorus, zinc and copper. These synergistic effects between biochar and AMF offer promising avenues for reducing chemical fertilizer dependence in sustainable agricultural systems^[73].

6. Nutrient Dynamics in Biochar-Amended Soils

6.1 Nitrogen Dynamics

Nitrogen (N) is the most important macronutrient for crop growth and is also the most prone to losses through leaching, volatilization and denitrification in intensive agricultural systems. Biochar influences soil nitrogen dynamics through multiple pathways: (i) physical retention of NH_4^+ within pores and on negatively charged surfaces, (ii) reduction of NO_3^- leaching due to improved soil structure and reduced water percolation, (iii) modulation of nitrification and denitrification rates and (iv) immobilization of N in the short term followed by gradual mineralization^[18].

Meta-analyses indicate that biochar application reduces N_2O emissions from soils by an average of 38-54%, representing both an environmental benefit (reduced greenhouse gas emissions) and an economic benefit (improved nitrogen use efficiency). The mechanisms involve reduction in nitrification rates in alkaline biochar-amended soils, physical adsorption of nitrification intermediates and improved soil aeration that reduces anaerobic microsites favorable for denitrification^[14, 54].

The effect of biochar on total plant-available nitrogen is, however, variable and context-dependent. High C:N ratio biochars may cause temporary N immobilization by stimulating microbial N uptake during their decomposition. It is therefore recommended that biochar be co-applied with nitrogen-rich amendments such as compost or animal manure to avoid short-term N deficiency in crops^[70].

6.2 Phosphorus Dynamics

Phosphorus (P) availability is a major constraint in many tropical agricultural soils due to strong fixation by iron and aluminum oxides in acidic soils, or calcium compounds in calcareous soils. Biochar can improve P availability through several mechanisms: (i) raising soil pH in acidic soils, reducing P fixation by Fe and Al, (ii) direct supply of P from nutrient-rich biochars (particularly manure-derived), (iii) stimulation of phosphate-solubilizing bacteria and phosphatase enzyme activity and (iv) complexation of Al and Fe on biochar surfaces, reducing their capacity to fix P^[26, 57].

However, the response is highly variable. In alkaline soils, biochar may further elevate pH to levels that promote Ca-P precipitation, reducing P availability. Additionally, the direct P content of most plant-residue biochars is relatively low (often < 0.5%), limiting their role as a direct P fertilizer^[21].

6.3 Potassium and Other Macronutrients

Many biochars, particularly those derived from plant materials, contain appreciable concentrations of potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S). Application of these biochars therefore directly adds these nutrients to the soil. The enhanced CEC of biochar-amended soils also improves the retention of these cations, reducing their leaching losses and maintaining higher concentrations in the soil solution^[28].

Studies on rice straw biochar application to paddy soils in South and Southeast Asia have reported significant increases in exchangeable K, Ca and Mg, as well as improved silicon availability - an important nutrient for rice that strengthens cell walls and improves resistance to biotic and abiotic stresses^[79].

6.4 Micronutrient Dynamics

The effect of biochar on micronutrient dynamics is complex and depends strongly on the specific micronutrient, soil pH changes and biochar properties. In acidic soils, biochar-induced pH elevation may reduce the solubility of zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn) - a beneficial outcome in soils contaminated with heavy metals, but potentially problematic in deficient soils [7].

Research has shown that biochar can effectively immobilize heavy metal contaminants such as cadmium (Cd), lead (Pb) and arsenic (As) in polluted soils, reducing their phytoavailability and minimizing food chain contamination. This application of biochar in heavy-metal remediation represents an important area where agricultural and environmental sustainability objectives converge [3, 56].

7. Effects of Biochar on Crop Performance

7.1 Root Development and Plant Growth

Biochar-induced improvements in soil physical properties - particularly reduced bulk density, improved porosity and enhanced water-holding capacity - create a more favorable rooting environment. Studies have documented significant improvements in root length, root surface area, root dry weight and lateral root branching in biochar-amended soils compared to unamended controls [61, 78]. These morphological improvements in root architecture facilitate greater exploration of the soil volume, improving the acquisition of water and immobile nutrients such as phosphorus.

Enhanced shoot growth, measured as plant height, leaf area index (LAI) and shoot dry weight, has been reported across a wide range of crops including wheat, maize, rice, soybean, groundnut, sorghum and vegetables. The growth improvements are generally attributed to the combined effects of improved water and nutrient availability, enhanced beneficial microbial activity and reduced soil physical and chemical stresses [50].

7.2 Crop Yield and Yield Components

Numerous field trials and meta-analyses have documented positive effects of biochar on crop yields. A landmark meta-analysis by [33] covering 103 studies reported an average yield increase of 10% across all crops, with the greatest responses in tropical regions with highly weathered, acidic and nutrient-poor soils. Subsequent meta-analyses by [19] and [47] confirmed these findings, with average yield increases ranging from 11% to 25% depending on crop type, soil type and biochar application rate.

For rice (*Oryza sativa*), one of the world's most important food crops and a staple in South Asian agriculture, biochar amendments have increased grain yield by 10-35% in diverse studies from India, China, Bangladesh and Indonesia. The positive responses are attributed to improved soil physical properties, enhanced silicon and potassium availability, reduced methane emissions from paddy soils and improved tolerance to flooding stress [30, 60].

Yield responses in wheat (*Triticum aestivum*) and maize (*Zea mays*) are also generally positive, particularly when biochar is combined with organic or inorganic fertilizers. The synergistic effect of biochar with conventional fertilizers - known as the "biochar-fertilizer synergy" - suggests that biochar can enhance fertilizer use efficiency, allowing the same or higher yields to be achieved with reduced fertilizer inputs [1].

7.3 Stress Tolerance - Drought, Salinity and Pathogens

Climate change is increasing the frequency and severity of abiotic stresses including drought, heat and salinity, which

represent major threats to global food security. Biochar has shown promising potential in mitigating these stresses. The improved WHC of biochar-amended soils directly reduces the severity of drought stress by maintaining higher soil moisture content during dry periods [52]. Additionally, biochar application has been associated with enhanced expression of stress-response genes and higher concentrations of protective osmolytes and antioxidant enzymes in stressed plants [24].

For salt-affected soils - a growing problem globally and particularly in irrigated agricultural regions of India - biochar has demonstrated effectiveness in reducing exchangeable sodium, improving soil structure and increasing the leaching of salts from the root zone. These effects are attributed to biochar's sorptive capacity for sodium ions and its ability to improve hydraulic conductivity and water movement through sodic soils [72].

Biochar has also shown biocontrol properties against soil-borne pathogens, including *Fusarium* species, *Pythium* and *Rhizoctonia*. The mechanisms include induction of systemic resistance in plants, modification of the soil microbiome toward beneficial organisms and adsorption of phytotoxic compounds produced by pathogens [22, 29].

8. Factors Influencing Biochar Effectiveness

The efficacy of biochar as a soil amendment is not universal and is modulated by a complex interplay of factors. The most critical determinants are: (i) biochar type (feedstock and pyrolysis conditions), which governs physical and chemical properties; (ii) application rate, with most studies reporting optimal responses at 5-20 t ha⁻¹ for most crops; (iii) soil characteristics, including initial pH, texture, organic matter content and fertility level; (iv) climate and cropping system; and (v) co-application with other amendments [35, 39].

The ageing of biochar in soil is another important factor. Fresh biochar may differ substantially in its reactivity from aged biochar that has undergone oxidation, weathering and interaction with soil minerals. Some studies suggest that the positive effects on soil and crop performance increase with time as biochar weathers and develops more surface functional groups [37].

Co-application strategies have received increasing research attention. Combining biochar with compost, vermicompost, nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, or chemical fertilizers often yields greater benefits than biochar alone. The complementary effects arise because biochar provides the physical habitat and stable carbon while other amendments supply the biologically active components and readily available nutrients [2, 8].

9. Carbon Sequestration and Environmental Benefits

Beyond direct agricultural benefits, biochar application to soil represents a potent strategy for long-term carbon sequestration. Biochar carbon, being predominantly composed of recalcitrant polycyclic aromatic structures, resists microbial decomposition and persists in soils for hundreds to thousands of years, effectively removing CO₂ from the atmosphere-plant cycle and storing it as stable soil carbon [41, 46].

Sustainable global biochar production could offset up to 12% of anthropogenic CO₂ emissions annually [77]. Additionally, biochar reduces greenhouse gas emissions from soils, including N₂O (by 38-54%) and CH₄ from paddy soils (by 12-50%), further enhancing its climate mitigation potential [34].

Biochar also contributes to improved water quality by reducing nutrient leaching and runoff from agricultural fields. Reduced nitrate and phosphate losses to water bodies can mitigate

eutrophication and protect aquatic ecosystem health ^[31]. In regions with significant groundwater dependence for drinking water, biochar-mediated reduction in agricultural pollutant leaching has important public health implications.

10. Research Gaps and Future Perspectives

Despite the substantial body of literature on biochar, several important knowledge gaps remain. First, the majority of studies are short-term (1-3 years) pot or small-plot experiments and long-term field-scale studies across diverse agro-climatic zones are critically needed to assess the durability and scalability of biochar effects ^[6]. Second, the economic feasibility of biochar production and application at the farm scale remains a significant barrier, particularly for smallholder farmers in developing countries who could benefit most from its use ^[65]. Third, there is a pressing need for standardized protocols for biochar production, characterization and application in research settings to enable meaningful cross-study comparisons. The wide variability in biochar properties and application methods has made it difficult to develop generalizable recommendations for farmers ^[74]. The International Biochar Initiative (IBI) and European Biochar Certificate (EBC) have made progress in this direction, but adoption of these standards is still limited. Fourth, the interactions between biochar and the soil microbiome deserve deeper investigation using advanced molecular tools such as metagenomics, metatranscriptomics and stable isotope probing to understand the mechanisms by which biochar modifies microbial community structure and function ^[38]. Fifth, the safety concerns related to potential contaminants (e.g., polycyclic aromatic hydrocarbons, heavy metals) in biochar produced from certain feedstocks or at suboptimal conditions warrant more attention to ensure food safety and environmental protection ^[13].

Future research should also explore the potential of engineered or modified biochars - such as those loaded with nutrients, inoculated with beneficial microorganisms, or co-composted - to enhance functionality beyond what is achievable with conventional biochar. The integration of biochar into precision agriculture frameworks, including variable-rate application guided by soil sensing technology and remote sensing, offers exciting possibilities for maximizing site-specific benefits ^[66].

11. Conclusion

Biochar is a multifunctional soil amendment with demonstrated capacity to improve soil physical, chemical and biological properties, enhance nutrient dynamics and boost crop performance across diverse agricultural systems. Its ability to simultaneously improve soil fertility, increase crop productivity, reduce environmental losses and sequester carbon makes it a uniquely valuable tool for sustainable agriculture. The weight of evidence from global research supports the use of biochar - particularly in tropical, acid, or degraded soils - as a cost-effective strategy for soil restoration and agricultural intensification.

However, the benefits of biochar are not universal and depend critically on biochar type, application rate, soil characteristics and management context. A one-size-fits-all approach is inappropriate; rather, biochar recommendations must be developed through site-specific research and extension activities. Investments in long-term field trials, economic analysis and policy support for biochar production infrastructure are essential to translate the scientific promise of biochar into widespread farmer adoption and tangible improvements in food security, soil health and climate resilience.

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