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Study on Nitrogen management through nano urea and conventional urea in wheat (*Triticum aestivum* L.)

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Abstract

Biochar, a carbon-rich byproduct of pyrolyzing organic materials, has gained widespread attention for its potential to enhance soil fertility and improve nutrient dynamics. This study explores the impact of biochar properties on soil nutrient retention, availability and overall fertility enhancement. Biochar's high surface area, porous structure, and variable cation exchange capacity (CEC) play crucial roles in improving soil nutrient retention, reducing nutrient leaching, and enhancing microbial activity. Additionally, biochar's to retain essential nutrients like nitrogen, phosphorus, and potassium has shown to reduce the dependency on synthetic fertilizers, promoting more sustainable agricultural practices. The influence of biochar on soil pH, water holding capacity and suppression of soil-borne pathogens further contribute to its effectiveness in enhancing soil health. Different feedstocks and pyrolysis conditions also result in biochar with varying properties, making it essential to tailor biochar application to specific soil types and agricultural needs. This review underscores the potential of biochar as versatile tool for improving soil nutrients dynamics, offering insights into it's use for sustainable soil management, enhance crop production, and environmental conservation. Future research into biochar's long-term effects on soil systems will be key to optimizing its benefits in diverse agricultural contexts.

Keywords: Biochar, Soil Fertility, Nutrient Dynamics, Sustainable Agriculture

Introduction

One of the most widely discussed aspects of biochar application in recent years is its potential influence on soil fertility and plant productivity (Allohverdi *et al.*, 2021) ^[3]. Agriculture continues to face challenges related to soil degradation, climate change, and the need for sustainable intensification, biochar has emerged as a promising soil amendment (Wang *et al.*, 2024) ^[31]. It recognized for its ability to enhance nutrient retention and improve soil structure, but it also offers a long-term solution for carbon sequestration, making it attractive from both agricultural and environmental perspectives (Lehmann, 2007).

However, it contributes to Soil fertility which plays a foundational role in supporting crop growth and sustaining food production systems. Plant productivity is directly dependent on the availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Wu *et al.*, 2024) ^[32]. The availability of these nutrients is regulated through complex biochemical transformations in the soil, which are driven by microbial activity, organic matter content, soil pH, moisture levels, and other physical-chemical properties (Marschner, 2006). Biochar significantly alters these soil parameters, its potential to influence nutrient cycling processes and enhance nutrient availability for plant uptake has become a focus of both research and practical interest Multiple field and laboratory experiments have demonstrated that biochar additions improve plant growth, particularly in nutrient-deficient or degraded soils (Hansson *et al.*, 2021) ^[9]. These benefits are often linked to improvements in soil pH, increased microbial biomass and activity, better soil moisture retention, and enhanced cation exchange capacity (Lehmann and Rondon, 2006; Atkinson *et al.*, 2010; Jeffery *et al.*, 2011). Moreover, the outcomes of biochar application are not always consistent. Studies vary in their findings, with some reporting minimal or even adverse effects on crop performance (Mundher Yaseen & Loui Alhalimi, 2025) ^[17].

These discrepancies are likely due to a range of variables, including differences in soil type, climatic conditions, crop species, biochar feedstock material, and application rates. As such, a one-size-fits-all approach to biochar application remains elusive, underscoring the importance of site-specific strategies (Osei *et al.*, 2025) ^[18].

Biochar itself is a stable, carbon-rich product derived from the thermal decomposition of organic biomass under conditions of limited oxygen a process known as pyrolysis (Sarkar *et al.*, 2024) ^[25]. During pyrolysis, not only is solid biochar produced, but also liquid bio-oils and syngas, which can be used as energy sources. A broad range of organic materials serve as feedstocks for biochar production, including agricultural residues, forestry waste, livestock manure, and even municipal organic waste (Sohi *et al.*, 2010) ^[29]. The physical and chemical properties of the resulting biochar such as its pH, porosity, elemental composition, and surface area are heavily influenced by both the type of feedstock used and the specific conditions under which pyrolysis occurs (e.g., temperature, heating rate, and duration).

These characteristics determine how biochar interacts with soil. For instance, its porous structure and high surface area make it highly effective at adsorbing nutrients, which may reduce leaching and increase nutrient retention in the root zone (Lee, n.d.) ^[13]. Biochar also serves as a favorable microhabitat for soil microorganisms, many of which play crucial roles in nutrient mineralization and other soil biological functions. Furthermore, the alkaline nature of many biochars can help ameliorate soil acidity, making certain nutrients more available for plant uptake. However, while biochar may enhance nutrient availability in the long term, its effects in the short term can sometimes be counterproductive (J. Ibrahim *et al.*, 2024) ^[11]. In particular, nitrogen immobilization where nitrogen becomes temporarily unavailable due to microbial assimilation or adsorption onto biochar surfaces has been observed in some systems, reducing immediate plant uptake (Premalatha *et al.*, 2023) ^[21].

Beyond nutrient cycling, biochar has garnered attention for its contributions to environmental sustainability (Vijay *et al.*, 2021) ^[30]. Its ability to sequester carbon in stable forms that are resistant to microbial breakdown means that biochar play a significant role in mitigating greenhouse gas emissions. Furthermore, its application has been shown to improve soil structure, reduce bulk density, and increase water-holding capacity features that contribute to improved soil resilience under stress conditions such as drought (Hassebrook *et al.*, n.d.) ^[10]. Biochar has also been studied for its potential to immobilize heavy metals and organic pollutants in contaminated soils, offering promise as a tool in environmental remediation efforts.

In recent years, biochar derived from organic waste materials has emerged as a particularly attractive option (Sachan *et al.*, 2110) ^[23]. Utilizing organic residues from agriculture, forestry, and urban waste streams for biochar production aligns with circular economy principles, contributing to waste reduction while enhancing soil fertility (Kamarudin *et al.*, 2022) ^[12]. Such biochars have demonstrated the ability to significantly modify the physical, chemical, and biological properties of soil, promoting plant health and increasing system resilience (Liang *et al.*, 2021) ^[15]. According to studies by Wang *et al.* (2020) and Abujabbar (2017), biochar from organic waste sources enhance soil microbial communities, improve nutrient cycling, and offer a sustainable alternative to conventional fertilizers and soil conditioners. Despite these benefits, it is important to note that the scientific understanding of biochar's influence on soil nutrient dynamics is still evolving. Some studies have found little to no improvement in plant growth following biochar

addition, while others have reported negative effects due to high application rates, unbalanced nutrient supply, or the use of inappropriate feedstocks (Sekaran *et al.*, 2022) ^[27]. These inconsistencies highlight the importance of conducting rigorous, site-specific assessments before large-scale application. They also emphasize the need for further research into the mechanisms by which biochar interacts with soil systems, including its long-term effects and synergistic interactions with other soil amendments such as compost or synthetic fertilizers (Sekaran *et al.*, 2022). To optimize biochar use in agricultural systems, more detailed knowledge is needed about its interactions with soil microbiota, its influence on nutrient transformation pathways, and the optimal application methods for different soil and crop types. Future research should aim to establish best practices for biochar integration in diverse agroecosystems, with particular attention to economic viability, environmental impact, and scalability. Long-term field trials, standardized methodologies, and interdisciplinary approaches will be crucial in addressing current knowledge gaps.

Methodology

This review investigates the impact of biochar on agriculture in Africa, with a focus on its soil enhancement properties, current application strategies, and recommendations for future use. A comprehensive literature review was conducted to gather insights into biochar utilization across sub-Saharan Africa (SSA). Targeted searches employed keywords such as soil amendment, biochar application, crop yield improvement, carbon sequestration, nutrient retention, soil health, and sustainable agriculture. Primary sources included ScienceDirect, Google Scholar, and ResearchGate. Initially, 712 studies were identified. Following a screening process that involved evaluating abstracts and full texts, relevant studies were selected. Of these, 29 studies each focused on the eastern, southern, and western regions, with one study specifically addressing countries in central Africa. Sixteen key findings were extracted and synthesized into the review for in-depth analysis.

Biochar production methods

Biochar can be prepared from a wide range of organic sources, which are mentioned in Table 1. There are mainly 4 methods of biochar preparation depending on the process, product, apparatus, and temperature during preparation: Pyrolysis, Hydrothermal Carbonization, Dry torrefaction, and Gasification (Allohverdi *et al.*, 2021) ^[3].

- **Slow**
≤5000C for 5- 30 min
- **Intermediate**
500- 6500C for 5 to 17 minutes
- **Hydrothermal carbonation**
180-2500C
2-10 MP pressure in presence of water
- **Flash**
900oC for 0.1 - 1 S
- **Pyrolysis**
Absence of oxygen
Oldest and common method
- **Gasification**
Torrefaction
200-3000C less production of biochar
- **Fast**
- 450- 6000C for 2 to 10 sec

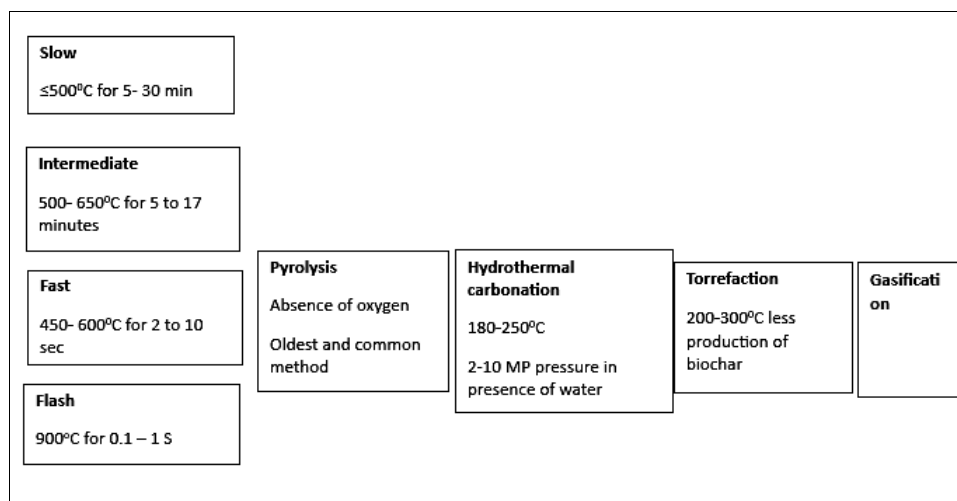


Fig 1: Overview of production techniques of Biochar

Biochar Production

Biochar Production

Biochar is a stable, carbon-rich substance produced through the thermochemical conversion of organic biomass in environments with limited oxygen (Wang *et al.*, 2024) [31]. It is primarily applied to soil with the goal of enhancing fertility, improving soil structure, and sequestering carbon, thereby offering both agricultural and environmental benefits (Jeffery *et al.*, 2011).

The production of biochar begins with a variety of organic feedstocks, including agricultural residues like crop straw and husks, livestock manure, forestry waste, and green urban waste. Prior to processing, these materials are usually cut into small pieces, typically less than 3 cm in size, to ensure even decomposition during thermal treatment (Hansson *et al.*, 2021) [9].

There are four primary methods for producing biochar, each differing based on temperature, oxygen availability, and processing time: pyrolysis, gasification, hydrothermal carbonization (HTC), and torrefaction (Pradana *et al.*, 2019) [20]. Pyrolysis is the most widely used method. It involves heating biomass at moderate to high temperatures ($350-700^{\circ}\text{C}$) in a low-oxygen environment (Saha *et al.*, n.d.) [24]. This process produces three main outputs: solid biochar, liquid bio-oil (including water and tar), and syngas (a mixture of carbon dioxide, carbon monoxide, hydrogen, and other gases) (Sohi *et al.*, 2010) [29].

In slow pyrolysis, the biomass is subjected to lower temperatures over a longer period (30 minutes to several hours), which results in a higher yield of biochar (Fenta, 2024) [6].

Fast pyrolysis, on the other hand, occurs at higher heating rates ($\geq 1000^{\circ}\text{C}/\text{min}$) over a much shorter duration usually just a few seconds favoring the production of bio-oil rather than biochar (A. Suresh & P. Raja Rao, 2021) [2].

Gasification involves partial oxidation of biomass at temperatures above 700°C . Although it generates mainly combustible gases, a small amount of biochar is produced as a by-product (Vijay *et al.*, 2021) [30].

Hydrothermal Carbonization (HTC) is a method suitable for wet biomass (). It processes the feedstock in hot, pressurized water (typically between $180-250^{\circ}\text{C}$), resulting in a carbon-rich solid product known as hydrochar (Wang *et al.*, 2024) [31]. This method eliminates the need to dry biomass beforehand.

Torrefaction is a milder version of pyrolysis. It occurs at lower temperatures ($200-300^{\circ}\text{C}$) in an inert or low-oxygen environment (Fakhar *et al.*, 2025) [5]. The process produces a brittle, energy-dense material with enhanced fuel properties, although the yield of biochar is typically lower compared to other methods (Hansson *et al.*, 2021) [9].

Biochar can be produced on a small scale using affordable, modified kilns or cookstoves at the household or farm level (Li *et al.*, 2023a) [14, 14]. It can also be produced on a larger scale in industrial pyrolysis plants that handle greater volumes of biomass with more advanced control systems (Gyanwali *et al.*, 2024a) [7]. The characteristics and nutrient content of the final biochar product are largely influenced by the type of feedstock

used and the specific conditions under which it is produced (Lu & Zong, 2018) [77].

Impact of Biochar on Soil Properties

Soil physicochemical properties play a critical role in regulating nutrient retention and availability, plant nutrient uptake, microbial dynamics, and overall crop productivity (Seleiman *et al.*, 2020) [93]. Extensive research has demonstrated that the application of biochar can significantly enhance the physical, chemical, and biological attributes of soils, thereby creating a more favorable rhizosphere environment for root development, nutrient absorption, and plant growth (Diatta *et al.*, 2020) [56].

Biochar amendments influence a broad range of soil physical properties (Schmidt *et al.*, 2021) [26]. These include improved water infiltration rates, increased water-holding capacity (WHC), enhanced soil aggregate stability, reduced susceptibility to erosion, and modifications in soil porosity and bulk density (Fenta, 2024) [6]. Biochar has been shown to mitigate soil compaction and hardening, which can otherwise restrict root penetration and aeration (Pandao *et al.*, 2023) [19].

Chemically, biochar alter soil pH often increases in acidic soils thus enhancing nutrient solubility and availability (Shareef & Zhao, 2017) [28]. It also contributes to an increase in cation exchange capacity (CEC), enabling soils to retain essential nutrients such as calcium, magnesium, potassium, and ammonium more effectively (Gyanwali *et al.*, 2024) [7]. Moreover, biochar promotes improved nutrient cycling by serving as a habitat for microbial communities and influencing key biogeochemical processes (Adekiya *et al.*, 2020) [34].

Soil Porosity

Soil porosity, defined as the proportion of void space between soil particles, is a fundamental property influencing key soil processes such as water retention and movement, air exchange, nutrient dynamics, and susceptibility to erosion (Arias *et al.*, 2023) [4]. Porosity is inherently linked to soil texture; clay-rich soils typically exhibit higher total porosity due to their fine particle size and greater surface area, while sandy soils possess lower porosity owing to larger particle size and limited aggregation potential (Rehman & Razzaq, 2017) [22].

The incorporation of biochar into soil systems has been widely reported to enhance porosity through several interrelated mechanisms (Moreno-Riascos & Ghneim-Herrera, 2020) [16]. These include a reduction in soil bulk density, improved aggregation, and decreased particle packing, which collectively

lead to the formation of additional intra- and inter-particle pore spaces (Blanco-Canqui, 2017) ^[44].

Empirical studies have quantified these effects. For instance, Zhang *et al.* (2017) observed a 23% increase in capillary porosity and a 24% increase in total porosity following biochar amendment, relative to unamended control soils. Similarly, Adekiya *et al.* (2020) ^[34] reported a substantial 65% enhancement in total porosity in biochar-treated soils compared to untreated controls. These findings suggest that biochar significantly alters soil pore architecture, potentially improving water and solute transport dynamics.

The extent of porosity improvement is not uniform across all soil types. Variability in response has been attributed to differences in soil texture, mineral composition, and the inherent physical characteristics of the biochar used (Li *et al.*, 2023b) ^[14]. Coarse-textured soils, such as sandy soils, tend to exhibit more pronounced increases in porosity upon biochar application compared to fine-textured (e.g., clayey) soils, likely due to their lower initial aggregation and bulk density (Alghamdi, 2018) ^[37]. Moreover, increases in porosity are often indirectly associated with reductions in bulk density (Yaashikaa *et al.*, 2020) ^[33]. For example, Blanco-Canqui (2017) ^[44] documented a porosity increase of up to 41% as a consequence of decreased bulk density following biochar incorporation. This inverse relationship underscores the role of biochar in enhancing soil structure and physical functionality through its porous nature and lightweight composition.

Soil Water Holding Capacity (WHC)

Water-holding capacity (WHC) is a critical soil property that reflects the maximum amount of water a soil can retain against gravitational forces, directly influencing plant-available water and overall crop performance (Liang *et al.*, 2021) ^[15]. Enhancing WHC is particularly important in water-limited environments or degraded soils with poor structure (Haddad *et al.*, 2024) ^[8].

Numerous field studies have demonstrated that biochar application can significantly improve soil water retention. This enhancement is primarily attributed to biochar's inherent porous structure and high specific surface area, which contribute to increased soil porosity and the creation of additional micropores and mesopores within the soil matrix (Razzaghi *et al.*, 2020) ^[90]. These pores serve as water reservoirs, improving the soil's ability to retain moisture for extended periods, especially under drought-prone conditions.

The effectiveness of biochar in enhancing WHC is influenced by its application rate, feedstock type, pyrolysis conditions, and the physicochemical characteristics of the receiving soil. For instance, Razzaghi *et al.* (2020) ^[90] observed a substantial increase in both soil water infiltration rate and moisture content following the application of biochar at 30 Mg ha⁻¹. These improvements were linked to enhanced soil structure and increased pore connectivity between biochar particles and soil aggregates (A Critical Review of Biochar Science and Policy-Executive Summary, 2011) ^[1]. Long-term studies further support the sustained benefits of biochar on soil water dynamics.

Kätterer *et al.* (2019) reported that the continuous application of biochar over a 10-year period resulted in a significant and persistent increase in WHC compared to control soils with no amendments. This finding defines the cumulative and enduring impact of biochar on soil physical properties over time.

In another study, Ndor *et al.* (2015) ^[84] investigated the short-term effects of sawdust- and rice husk-derived biochar applied at rates of 5 to 10 Mg ha⁻¹. The results showed a 10.8% increase in soil moisture content relative to unamended soils, demonstrating

that even moderate biochar additions can yield measurable improvements in soil water retention.

Soil Organic Matter and Soil Organic Carbon Content

Soil organic matter (SOM) is a fundamental component of soil health, playing a crucial role in nutrient cycling, microbial activity, soil structure, and overall soil fertility (Battaglia *et al.*, 2021). Increasing SOM levels is vital for sustaining soil productivity, particularly in degraded or low-carbon soils. Biochar, due to its high carbon content and stable structure, has been widely recognized for its capacity to enhance SOM and soil organic carbon (SOC) through both direct and indirect mechanisms (Arias *et al.*, 2023) ^[4].

Research studies have demonstrated that the application of biochar leads to a measurable increase in total soil carbon content, improved water-holding capacity, and greater soil aggregate formation and stability (Diatla *et al.*, 2020) ^[56]. These improvements are largely attributed to the recalcitrant nature of biochar carbon, which resists microbial decomposition and contributes to long-term carbon sequestration in soil.

Adekiya *et al.* (2020) ^[34] observed that the application of hardwood biochar at 30 Mg ha⁻¹ resulted in a significant increase in organic matter content by approximately 77%, 18%, and 9% when compared to unamended soil, and to lower application rates of 10 and 20 Mg ha⁻¹, respectively, over a two-year period. This finding highlights the dose-dependent effect of biochar on SOM enrichment.

The effectiveness of biochar in increasing SOM also depends on its chemical composition and the nature of the feedstock (Rehman & Razzaq, 2017) ^[22]. Biochar retains a portion of the original organic constituents from the biomass, contributing to the overall organic input into the soil. Zhang *et al.* (2017) reported that soil organic carbon content increased from 3.1 mg kg⁻¹ to 4.9 mg kg⁻¹ following biochar amendment, indicating the contribution of biochar-derived carbon to total SOC.

Similarly, Yao *et al.* (2017) ^[104] demonstrated substantial improvements in SOM and SOC following the application of maize stalk biochar at rates of 50, 100, and 200 Mg ha⁻¹. These results underscore the potential of biochar, particularly at higher application rates, to act as a stable carbon reservoir while simultaneously enhancing the organic matter pool in the soil.

Soil Bulk Density

Soil density is an indicator of soil health, compaction and soil aeration influences water infiltration, rooting depth of plants and movement of nutrients (Alghamdi, A.G, 2018) ^[37]. Soils with high bulk density have a lower capacity than soils. Soils with high bulk density have a lower capacity than soils with low bulk density. This can increase the absorbing of water and can cause a high penetration resistance to plant roots into the soil. In a recent review, Omondi *et al.* (2016) ^[87] concluded that biochar addition decreased soil bulk density between 3 and 31% in 19 out of 22 soils. Soil texture also plays an important role in the resulting bulk density after biochar application.

Oil texture also plays an important role in the resulting bulk density after biochar application. In general, the application of biochar to the soil results in a greater reduction in the bulk density in coarse than in fine-textured soils (Blanco-Canqui, H, 2017) ^[44]. It is hypothesized that at least two mechanisms are responsible for reductions in the soil bulk density after biochar application. Firstly, soil has a higher density (~1.25gcm⁻³) than biochar (0.6g cm⁻³). Thus, biochar applications can reduce the soil bulk density through a dilution effect. Secondly, biochar can reduce the bulk density of soil in the long term in part due to the

complex interactions that it establishes with soil particles, which further improve soil aggregation and porosity.

Soil pH

Soil pH affects the mobility and availability of different nutrients and chemical elements in the soil. Generally, application of biochar to soil increases the soil pH, although changes are strongly driven by the soil type, feedstock material, and the liming value of biochar (Tian *et al.*, 2017) Martinsen *et al.* (2015)) applied biochar rates derived from oil palm (*Elaeis guineensis*) shell, cacao shell (*Theobroma cacao L.*), and rice husk (*Oryza sativa L.*) to 31 acidic soils. They observed an increase in soil pH from 4.7 to 5 when cacao shell biochar was applied, which was greater than those obtained from oil palm shell and rice husk.

In general, biochars are alkaline in nature, and their alkalinity increases with the rise in the temperature during the pyrolysis process (Shakya, A *et al.* 2020) [96]. High temperature pyrolysis removes the carboxyl, formyl, or hydroxyl groups and increases the concentration of inorganic elements and basic oxides. In addition, the pH of biochars depends on the feedstock materials. For example, biochar produced from lignin-rich material, for instance, nut and shell biomass, has a pH around 8, while biochar derived from manure, waste biomass, and algae typically has the highest pH levels (~9.5). When the alkaline biochar with pH 7-9 is incorporated into the acidic soil (pH<7), it increases the soil pH and decreases the mobility of cationic metals such as Copper (Cu), Zinc (Zn) Cadmium (Cd) and

Mercury (Hg) in the soils because of less competition between metal ions H^+ ions for cation exchange sites (Aller, M.F. 2026) [38].

Cation Exchange Capacity (CEC)

Biochar with high CEC can retain more nutrients, reduce nutrient leaching and increase the absorption of ammonium (NH_4^+), K^+ , calcium (Ca^{2+}), and magnesium (Mg^{2+}) from soils to plant roots by releasing H^+ to balance the charge in the soil (Seleiman, M.F *et al.* 2020) [93]. The CEC of biochar decreases with the increment in the pyrolysis temperature due to the loss of functional negatively charged groups and low pyrolysis temperatures (300-450 °C).

The variability in CEC of biochar also depends on feedstock sources and the specific functional groups formed during pyrolysis that can affect the surface properties of the biochar (Suliman, W., *et al.* 2016). For example, the CEC of biochar produced from pig manure was lower (32.7 cmol/kg) compared to chicken manure biochar (81.4 cmol/kg) pyrolyzed at 500 °C. Although CEC is a natural and inherent characteristic of any soil, it is not easily changed by management. However, many studies have shown that biochar amendment can increase the CEC of soil (Karimi, A., *et al.* 2020) [71], which could be due to the presence of strong carboxylic and phenolic functional groups with negative charge on the surface of biochar particles (Palansooniya, K.N., *et al.* 2019). Zhang *et al.* (2017) reported a 21% increase in the soil CEC after biochar application compared to un-amended soil (control).

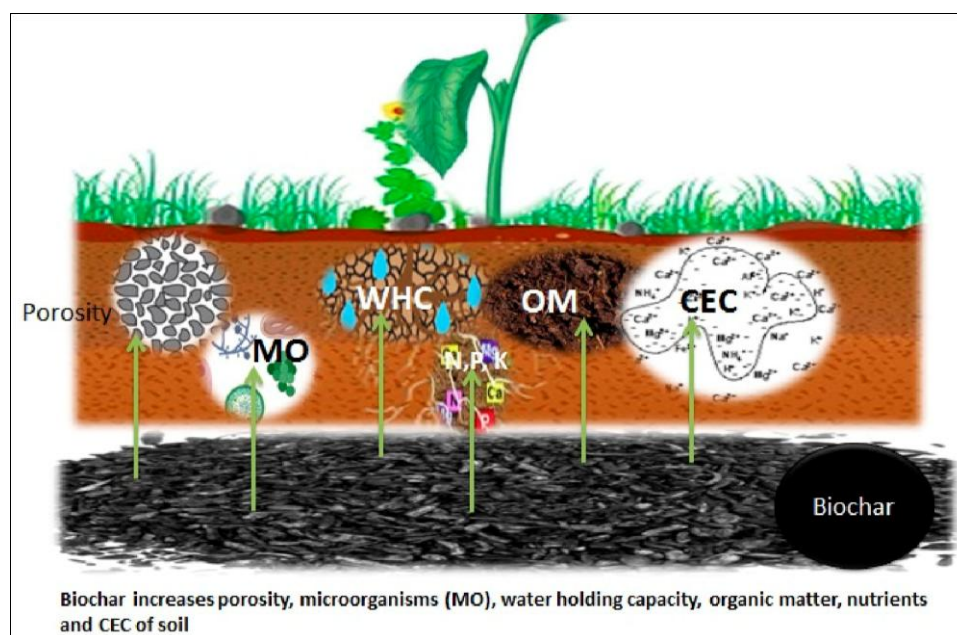


Fig 2: Biochar increase microorganisms (MO), water holding capacity (WHC), organic matter (OM) porosity and cation exchange capacity (CEC)

Future Uses of Biochar in Sustainable Agriculture

Biochar, a stable and carbon-rich material derived from the pyrolysis of organic biomass, is emerging as a valuable tool in the advancement of sustainable agricultural practices. Owing to its multifaceted agronomic and environmental benefits ranging from improved soil health and nutrient retention to enhanced water management and carbon sequestration biochar is positioned to play a transformative role in future agricultural systems. As scientific understanding of biochar's physicochemical properties continues to expand, so too does its potential for broader and more targeted applications in

agriculture. Future developments may include the formulation of biochar-based soil amendments tailored to specific crop and soil requirements, integration into precision agriculture technologies, and its use as a carrier for beneficial microbes or slow-release fertilizers.

However, the localized and decentralized nature of biochar production offers a unique opportunity for rural economic development. Because biochar systems can be scaled to suit smallholder or community-level operations near biomass sources, they can stimulate local economies, reduce waste, and support sustainable land management strategies.

Conclusion

The yield and quality of biochar from the thermochemical conversion processes of biomass are vastly different due to differences in the amount of oxygen available, heating rate, and reaction temperature. Generally, the yield of biochar decreases with faster heating rate or more oxygen available. Beneficial impacts of biochar amendments in agro and forestry systems, such as improved soil health, better plant growth, carbon sequestration and reduced greenhouse gas emissions have been widely reported, but mixed or opposite results do exist, thus the benefits of biochar application are often limited to particular conditions such as the types of biochar, rates of application, soil type and conditions, and crop species. Systematic investigations are needed to elucidate the relationships among biochar production technologies, biochar properties, and biochar performance in agro and forestry systems.

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