BIOCHAR

SOLID CARBON FOR SUSTAINABLE AGRICULTURE

Editors:
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Biochar - Solid Carbon for Sustainable Agriculture

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PREFACE

In the ever-evolving landscape of agriculture and environmental sustainability, biochar stands as a remarkable, yet often underestimated, ally. As our world grapples with the challenges of feeding a growing population, mitigating the impacts of climate change, and restoring ecosystems tainted by contaminants, the role of biochar has emerged as a beacon of hope. This reference book, "Biochar: Solid Carbon for Sustainable Agriculture," aims to shed light on the profound significance of biochar in addressing these multifaceted concerns.

Biochar, a carbon-rich substance formed through the pyrolysis of organic materials, possesses the unique ability to transform how we interact with our environment. Its origins can be traced back through centuries of trial and error, as humans sought to enhance soil fertility and reduce waste. Today, we have embarked on a journey to unlock the full potential of biochar in the context of contemporary agricultural practices and environmental management.

This book is the culmination of efforts from a diverse group of writers who share an interdisciplinary understanding of biochar. We have endeavored to create a platform where knowledge, research, and experience converge to offer a holistic exploration of biochar's applications and limitations. Our collective goal is to provide readers with a comprehensive guide that not only illuminates the art and science of biochar production but also delves into the intricate web of its effects on soil, agriculture, ecosystems, and the global environment.

Within these pages, you will find an in-depth exploration of the physical, chemical, and biological properties of biochar, as well as its role in the sequestration of heavy metals and greenhouse gases. We investigate how biochar influences soil organisms, from microorganisms to macroorganisms, and the consequent changes in enzyme activities. The book also addresses the tangible benefits of biochar in boosting agricultural productivity, enhancing crop yields, and controlling plant pathogens while simultaneously addressing its potential limitations and challenges.

The journey you are about to embark on is one of discovery, innovation, and a shared commitment to a more sustainable world. It is our hope that "Biochar: Solid Carbon for Sustainable Agriculture" serves as both a reference point and an inspiration for working teams worldwide as they seek to determine outcomes and pinpoint future research needs. Together, we can harness the power of solid carbon in the form of biochar to cultivate a more resilient, productive, and harmonious relationship with our planet.

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ENDORSEMENT

In "Biochar - Solid Carbon for Sustainable Agriculture," editors Rubab Sarfraz and Christopher Rensing have compiled a groundbreaking exploration into one of the most promising solutions for our agricultural and environmental challenges. This meticulously researched and thoughtfully crafted book not only sheds light on the transformative potential of biochar but also serves as a roadmap for its widespread adoption.

Biochar, with its ability to improve soil fertility, sequester carbon, and mitigate climate change, represents a beacon of hope in our quest for sustainable agriculture. Through a blend of scientific expertise and practical insights, Sarfraz and co- have curated a collection of chapters that offer a comprehensive understanding of biochar's applications—from its production and properties to its impact on crop productivity and ecosystem health as well as covering the cost dynamics.

What sets this book apart is its accessibility and relevance. Whether you're a seasoned researcher, a farmer looking to enhance soil health, or a policymaker seeking innovative solutions, "Biochar - Solid Carbon for Sustainable Agriculture" provides invaluable insights that can inform decision-making and drive meaningful change. Moreover, by addressing not only the technical aspects but also the socioeconomic and policy dimensions of biochar adoption, this book fosters a holistic perspective that is essential for effective implementation.

As we confront the urgent challenges of climate change and food security, "Biochar - Solid Carbon for Sustainable Agriculture" emerges as a timely and indispensable resource. Editor and authors have done a great job to bring together a diverse array of perspectives, making this book a must-read for anyone passionate about building a more sustainable future.

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CHAPTER 1

The Science of Biochar Production: Understanding the Formation and Characteristics of Biochar

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Abstract: Mineral fertilizers have been associated with the accelerated decomposition of organic matter in the soil. This rapid decomposition primarily affects organic materials such as plant residues and other organic substances present in the soil. Biochar, produced by the pyrolysis of biomass, offers a sustainable solution to enhance soil fertility and crop productivity. Biochar has a one of a kind potential to improve soil health and counteract global climate change. Its distinct qualities, such as high carbon content and the potential to promote soil health, make it an efficient, environmentally friendly and cost-effective material for overcoming global food security and increasing temperatures. Biochar can be produced using a variety of biomass materials and at various temperatures, resulting in a wide range of variations in the final product. Because of variations in its physicochemical attributes, such as microporosity, surface area and pH, biochar can be customized for specific applications. The pyrolysis temperature, heating rate, residence time, and biomass used during production all have a strong influence on the structural configuration and elemental composition of biochar. According to research, biochar produced at high pyrolysis temperatures has high ash, phosphorus, and potassium concentrations. Furthermore, many important macro and micronutrients, such as calcium, magnesium, iron, and zinc, have been found to be positively associated with increasing temperature. Biochar produced at low pyrolysis temperatures, on the other hand, provides relatively more available nutrients in the soil and can help to reduce carbon dioxide emissions. Biochar produced at high pyrolysis temperatures has a stronger affinity for organic contaminants due to its increased surface area, hydrophobicity, microporosity, high pH, and low dissolved organic carbon. It is important to note that the properties of biochar

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should be thoroughly assessed before application due to the wide variability of biomass resources and pyrolysis conditions. Furthermore, biochar production should be tailored to the intended application in soil to maximize its efficacy.

Keywords: Biochar production, Biomass materials, Crop productivity, Carbon sequestration, Elemental composition, Microporosity, Macro and micronutrients, Nutritional properties, Organic pollutants, Pyrolysis temperature, Soil fertility, Surface area, Structural configuration.

INTRODUCTION

Since the green revolution, greater use of agrochemical-based crop production methods, as well as rapid industrialization, has raised crop yields while maintaining nutritional levels; however, excessive use of mineral fertilizers has resulted in rapid decomposition of organic matter, stimulating the microbial activity ultimately leading to the quicker breakdown of organic matter. As a consequence, this accelerated decomposition can influence the overall dynamics of soil organic carbon and nutrient cycling [1 - 3]. Extensive research has been conducted to restore degraded agricultural soils and natural resources to address these issues [4, 5]. Organic residues, such as compost, manure, and other organic materials, have been shown to be a viable alternative to mineral fertilization [6, 7]. However, because of their low nutritional content and rapid degradation rate, these materials must be used in large amounts.

Biochar's application in environmental management has gained significant attention in recent years due to its numerous benefits. Biochar is a porous, fine-grained material that is employed in the soil to increase its fertility. It is produced in a sustainable manner as a byproduct of biomass bioenergy. Biochar has important environmental and agricultural implications due to its versatility and heterogeneity. Its physicochemical properties, such as high adsorption potential, buffering, cation exchange capacity and specific surface area are critical in evaluating the scope and direction of the responses triggered by its application.

Furthermore, the type of biomass and biochar production underlying pyrolysis conditions have a significant impact on its physicochemical and structural properties, such as functional groups, surface area, polarity and pH, which eventually define its overall surface properties [8, 9]. These changes in biochar characteristics have a major impact on its efficiency in improving soil fertility, nutritional status, and agricultural productivity. Biochar application recovers the soil's chemical, physical, and biological properties [5], and actions as a soil conditioner, cumulative soil water holding capacity and nutrient levels, resulting in not only improved seed germination but also crop growth and production [10, 11]. These biochar properties also increase the soil microbial population, which contributes to overall positive effects on soil health [12].

Origin of Biochar

The production of biochar, also known as Terra Preta, is an ancient practice that dates back to Egyptian societies over 70 centuries ago. While the primary purpose of biochar production in ancient Egypt was not solely for agricultural use, the liquid wood tars produced through charring processes were used to embalm the bodies of the dead (Emrich, 1985). The term “black earth of the Indios” is commonly used to refer to a specific type of soil that has attracted the scientific community’s consideration across the world. It is thought that Terra Preta is the outcome of indigenous cultures modifying the soil through activities such as cooking and agriculture [13].

The Terra Preta discovery occurred in the Brazilian Amazon, where large amounts of pottery and human-made objects were found in areas with soil that greatly differed from the surrounding land despite similar mineralogy and texture [14]. Unlike the typical, unproductive soils of the Amazon rainforest, Terra Preta is characterized by its black color, alkaline pH, and rich microorganisms [15]. Terra Preta soils have higher total carbon storage, approximately 250 t C ha^{-1} m^{-1}, than the typical value (100 t C ha^{-1} m^{-1}) in adjacent soils [16, 17].

This soil is represented by a high charcoal content, more than 70 times that of the surrounding soil, and can be found at a depth of 40-80 cm. Over thousands of years, it is believed to be the result of the local people's use of the “slash and char strategy”, introducing plant remains into the soil through incomplete combustion [14]. Terra Preta's carbonaceous fraction is chemically and microbiologically stable due to its complicated aromatic polycyclic chemistry, which might remain in the environment for decades. As it oxidizes on the surface, it produces carboxylic groups, increasing its capacity to retain nutrients.

This “black fortune” that defines a substantial portion of the Amazon basin and other South American regions is thought to be ascribed to the Pre-Columbian civilization that inhabited the Amazon between 2500 and 500 BC. West Africa and Borneo were additionally characterized as having equivalent soils [18].

Production and Formation of Biochar

Biochar is a substance made up of components like hydrogen, carbon, sulfur, nitrogen, and oxygen, as well as minerals in the ash fraction [19]. It is formed during pyrolysis, which is the thermal decomposition of biomass in a low-oxygen environment. It is highly porous, black, fine-grained, with a high surface area,

CHAPTER 2

Effect of Biochar on Soil Properties

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Abstract: Soil is the most significant source and home of many nutrients and microflora. There is an urgent need to maintain sustainable agricultural production methods due to the rapid deterioration of agricultural areas and soil quality because of population growth and excessive use of chemical fertilizers. Biochar is a solid, carbonaceous material produced under a limited oxygen environment. Nowadays, it is considered a potential amendment in comparison to inorganic fertilizers as they affect soil health. It not only improves plant growth but also maintains soil health by optimizing soil's physical (*e.g.*, bulk density, surface area, hydraulic properties, and water availability) and chemical properties (*e.g.*, pH, electrical conductivity, cation exchange capacity, and organic matter). Keeping in view the effects of biochar on soil quality indicators, in this chapter, we will discuss the potential of biochar in restoring soil physical and chemical health.

Keywords: Biochar, Soil health indicators, Soil physical properties, Soil chemical properties.

INTRODUCTION

Plants need a variety of soil nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). Since nutrients are not replenished in the soil after crop harvest, nutrient levels of the soil may gradually decline with the passage of time. Many soils are not only deficient in macronutrients like NPK but also in micronutrients like boron, zinc, copper, and iron, as well as secondary nutrients like sulfur, calcium, and magnesium [1]. Therefore, a large amount of chemical fertilizers are added to the soil to make up for the shortfalls; however, only a small part of the water-soluble nutrients is absorbed by plants, and the rest is converted to an insoluble form, requiring constant fertilization. Last but not least, the widespread chemical fertilizer use has caused the environment to deteriorate, resulting in an

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endless list of issues. Long-term degradation of soil fertility occurs in addition to lowering crop nutrient composition [2, 3].

In addition to fertilizers, pesticides are the primary enemy of agriculture, and their harmful environmental effects are solely responsible for altering the microbial characteristics of the soil. High fertilizer and pesticide inputs and their long-term persistence in the soil negatively affect the soil microbiome, degrade soil health, and significantly reduce the total microbial biomass and mushrooms [4]. The structural diversity and pre-dominant microbial groups in agricultural soils changed after long-term treatment with inorganic fertilizers (N and NPK) and/or organic fertilizers, as described by Wu *et al*. (2012). Contrarily, biofertilizers can revitalize the soil by increasing soil fertility, making them an effective tool for sustainable agriculture and less stressful for agroecosystems [5]. In addition, from a remedial perspective, the use of organic soil amendments is generally justified by their relatively low cost, which often requires other treatment methods (landfilling, burning, *etc.*). Soil improvement properties should include high bonding ability, environmental safety, and no adverse impact on soil structure, soil fertility, or the ecosystem [6]. The removal of heavy metal pollutants from the soil and the improvement of soil quality have both been attributed to the use of biochar [7]. Biochar is a carbon-rich organic material produced as a by-product of the biomass by the pyrolysis process at high temperatures and low oxygen. The process of pyrolysis yields biochar as well as oil and gas as by-products. However, the processing conditions have an impact on the generation of these materials. Biochar is widely suggested as a soil organic input that influences soil carbon sequestration as well as for changing its physico-chemical and biological properties primarily by carbonizing organic wastes [8]. Applying biochar as a soil amendment improves soil quality, encourages plant growth, and enhances carbon storage because of its highly recalcitrant carbon contents [9]. Adding biochar can increase the amount of organic matter in soils, improving soil fertility and nutritional status. Biochar application to soil can change its density, texture, porosity, and particle size distribution [8]. Biochar can act as a shelter for beneficial soil microorganisms like mycorrhiza and bacteria and can have an impact on the binding of significant nutritional cations and anions because of its extremely porous structure and high surface area. Pieces of evidence suggest that applying biochar enhanced water quality, decreased nutrient leaching, decreased soil acidity, increased water retention, and decreased the requirement for irrigation, fertilizer, and water. Application of biochar considerably enhanced plant uptake of essential nutrients and growth yield, especially when additional nutrients were present [10]. This method has attracted increasing interest as a long-term strategy to improve the properties of adversely degraded tropical soils [11]. The physical characteristics of soil, such as bulk density (BD), water holding capacity (WHC), surface area, and water repellency (PR), are modified with biochar, which is usually highly porous and exhibits a high surface area [12]. As a result, biochar can be very helpful in creating a more sustainable agricultural system. The use of biochar amendment has been linked to a number of benefits, including the ability to restore contaminated soil [13] and enhance the growth and yields of crops without environmental deterioration. Because of the beneficial effects of biochar on soil quality and plant growth, it is a good strategy for addressing nutrient deficiencies and can be used to enhance farm-scale nutrient cycles. Exploring the favorable effects of biochar amendment on improving soil stability, soil health indicators such as physical and chemical properties, and plant growth promotion has thus been given full attention (Fig. **1**).

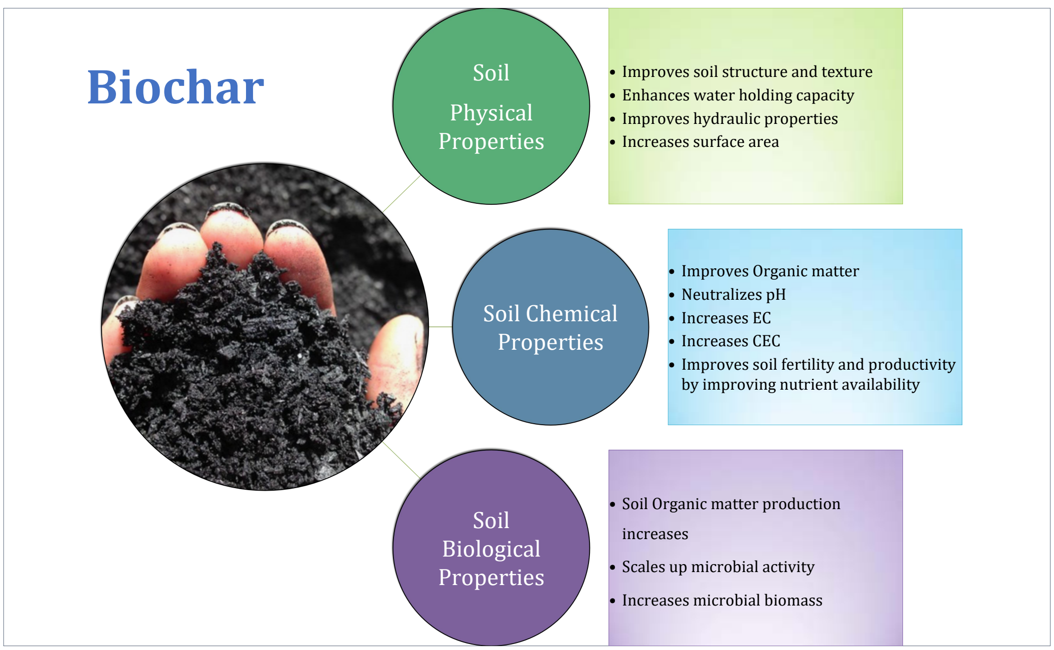

Fig. (1). Effect of biochar on soil properties.

What Does Physical Soil Health Mean?

Physical, chemical, and biological components are generally regarded as the three main aspects of soil health, also known as soil quality (Fig. **1**). It is regarded as crucial for determining management strategies for sustainable land use as well as for gauging the degree of land degradation or amelioration.

CHAPTER 3

Impact of Biochar on Soil Organisms

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Abstract: Soil organisms are very important to improve soil fertility and maintain a natural balance between soil nutrient cycles, enzyme activities and biological transformation of complex substances. Typically, one gram of soil contains more than 90 million bacteria, which helps plants in nutrient uptake by converting them into forms that are available to the plants. People tend to think negatively of microbes because they are unaware of how important they are, even though they frequently behave as disease-causing agents. Similarly, the role of soil macroorganisms in improving soil structure and nutrient movement is equally significant. The use of biochar as an exuberant carrier of soil organisms in the soil ecosystem has been widely studied. Therefore, in this chapter, we will emphasis the types and functions of macro and microorganisms in the soil, the impact of biochar on soil organisms, nutrient cycling and enzyme activities.

Keywords: Biochar, Enzymes Activities, Macroorganisms, Microorganisms, Soil Nutrient Cycle.

INTRODUCTION

A whole "biological cosmos" can be found in just one gram of dirt. In this chapter, we will learn how the soil biota in this microcosm regulates greenhouse gases, alters the energy cycle, improves soil health, and shapes their habitat.

In his famous poem, *The Auguries of Innocence*, the poet William Blake wrote:

"To see a world in a grain of sand,

And a heaven in a wild flower,

Hold infinity in the palm of your hand,

And eternity in an hour."

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A single teaspoon of rich soil contains all the domains (Bacteria, Archaea, and Eukarya) and elements of life; this tiny amount might be considered the "biological cosmos". Six essential elements—hydrogen (H), carbon (C), nitrogen (N), phosphorus (P), oxygen (O), and sulphur (S)— are altered by soil organisms and are hence necessary for the majority of Earth's life (the soil biota). The soil consists of a wide variety of both living and non-living materials. There are varied amounts of solids, gases, liquids, and organic matter dispersed throughout its many levels. About 40% of soil is made up of rocks and minerals, 25% is gas, 25% is liquid, and 10% is organic matter, according to a general analysis [1].

The mutually beneficial association creates a soil ecosystem with a variety of unique characteristics. Thereby, plants might feel safe from potential predators. Several nutrients are recycled in soil, and it also serves as a filter that cleans water. Microfauna and microorganisms make up the smaller group, whereas higher animals and plants make up the larger group of soil organisms [2]. Bacteria, fungi, and protozoa are among the most abundant soil microorganisms.

Macrofauna consists of animals like nematodes, arthropods, mollusks, and oligochaeta. Many other creatures spend some time in the soil, but they do so primarily for reproduction or nutrition and are therefore not considered. All of the aforementioned creatures are crucial to the process of soil formation and the soil ecosystem. More often than not, it is the microbes of the lower trophic levels on which the larger organisms rely. Therefore, microorganisms will be discussed first to provide background.

Bacteria are among the most vital members of the soil community. These microbes, which consist of just a single cell, are crucial to the functioning of the larger ecosystem [1, 2]. One of their functions is to break down dead plants and animal remains. The cells of the bacteria are capable of transforming the nutrients in these waste products from an unusable form into a useful one. Bacteria are able to transform nitrogen, which is a vital nutrient [3]. By utilizing cellular processes, nitrogen-fixing bacteria are able to convert atmospheric nitrogen (N_2) to the more usable form, ammonia (NH^{3+}). Ammonia (NH^{3+}) and water (H_2O) are combined by nitrifying bacteria to produce ammonium ion (NH^{4+}) and nitrate (NO^{3-}). Soil protozoa play a role in bringing ammonium to plant roots and other soil organisms [4]. Ammonia is released because these organisms release nitrogen from the bacteria they eat but do not consume. Because of how essential it is to plant growth, humans developed an industrial procedure to incorporate additional nitrogen into fertilizers.

Bacteria called denitrifiers are responsible for releasing N_2 gas back into the air. Bacteria may break down a wide variety of substances. Bacteria belonging to the phylum Actinobacteria (also known as Actinomycetes) are responsible for breaking down chitin, cellulose, and other complex substances found in decomposing plants, animals, and fungi [5]. Because of their sturdy composition, these materials resist degradation by living organisms. The bacteria secrete an enzyme that breaks down complex polymers like chitin into more basic building blocks like sugar and ammonia. Bacteria known as actinomycetes were once classified asfungi. They were given that name because they, like fungi, produce hyphae and thrive in situations where most bacteria perish, such as acidic or dry environments. They were named actinobacteria after being re-classified. In fact, the presence of these bacteria in the soil is a positive sign of environmental health because of the earthy smell they produce. By breaking down organic matter and providing plants with the nitrogen they require, bacteria like these play a crucial role in keeping soils healthy. In the soil ecosystem, fungi play a similar role.

They proliferate in locations where bacteria cannot survive, like those that are acidic, low in nitrogen, dry, and dense in complex carbohydrates (bacteria cannot break them down). Decomposing difficult organic compounds like chitin, cellulose, keratin, and lignins is a specialized task that fungi excel at. Fungi, like actinobacteria, can create enzymes that break down these powerful chemicals into sugars, making them digestible to a wider variety of organisms [6]. Fungi play a dual role in the ecosystem, both as decomposers and as providers of nutrients to other creatures, in this case, plants. Mycorrhiza refers to the symbiotic interaction between fungi and plants. Roots may become colonised by the fungi, or the fungi may become endophytic (growing inside the root). Fungal access to and delivery of vital nutrients is enhanced by the hyphae's large surface area relative to their volume. In return, the plants supply the fungi with glucose for energy. As if their role in transforming nutrients into usable forms was not already evident, these microbes are also relied upon by many of the soil's larger animals as a primary source of nutrition. Macrofauna require the nutrients that bacteria create.

The earthworm is the most common and useful member of the soil's mammalian community. The segmented worms known as oligochaeta are a type of annelid that helps create the typical soil structure. Earthworms create shafts and tunnels in the ground. These crevices relax the soil structure, allowing other species to move around more freely and reach previously inaccessible locations. Many species, including earthworms, rely on soil with high moisture content, and this moisture is increased by the addition of water to the voids in the soil [7]. Substantial reductions in surface runoff can result from water being absorbed by the soil. Earthworms consume soil and dead plant material as they make shafts or tunnels underground. Castings are the by-products resulting from the digestion of these useful nutrients. It includes bacteria, fungi, and nutrients like N, P, K, Ca and Mg, which were made from decomposing organic matter. Castings include

CHAPTER 4

Impact of Biochar on Plant Pathogen Control

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Abstract: It has been reported that organic amendments can lessen the impact of pathogen-caused plant diseases. Researchers have been looking for alternative materials for growth mixes for plants, especially for pots, as a result of the growing demand for substrates without soil and the escalating environmental concerns associated with the utilization of resources that are not renewable, such as peat. A variety of biochar effects help to prevent root or foliar fungal infections by altering root exudates, soil characteristics, and nutrient availability, all of which influence the proliferation of antagonistic microorganisms. Biochar's induction of systemic plant defenses in the roots to combat foliar pathogenic fungus and the activation of stress hormone responses are all indicators of coordinated hormonal transmission within the plant. Additionally, nematodes and pest insects are controlled by biochar. The primary mechanisms of action of plant-parasitic nematodes are changes in the diversity of soil microbes, the release of nematicidal chemicals, and the development of plant defenses. In this chapter, we looked at how the health and disease of plants are affected by biochar as a component of the growing medium. Biochar treatments show a lot of promise, according to this study, but not enough research has been done to support their widespread use as a soil supplement in modern agricultural systems. More research on the processes that drive biochar disease suppression and long-term field tests are required to make biochar a safe, effective, and cost-effective tool for controlling plant diseases.

Keywords: Pyrolysis, Plant Pathogen, Soil amendment, Soil microbes, Stress hormone.

INTRODUCTION

According to Lehmann [1], biochar is a carbon-rich material formed by carbonizing biomass at high temperatures and in an oxygen-deficient environ-

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ment, hence pyrolyzing the organic matter [2]. This process occurs in a pyrolysis chamber and changes organic material into a variety of compounds, which could be solid, liquid or in gaseous form. The solid component, known as biochar, is made up of inorganic elements such as fixed carbon [3, 4].

Carbon-rich soil amendments were first identified as advantageous to Brazilian soils in the 1870s [5, 6]. Carbon sequestration [7], decreased greenhouse gas emissions [8 - 10] and energy generation are some benefits of utilizing biochar as a soil amendment [11]. Among the most frequently used biomass sources to make biochar are animal and vegetable waste, algae, sewage sludge, and agricultural and forestry waste [12].

Because of physical and chemical characteristics, which are very sensitive to feedstock and pyrolysis conditions, biochar may have an impact on soil fertility. Nutrient availability, pH, ash content, pore size, density, EC, CEC and hydrophobicity are all features of biochar [13 - 15]. Carbon (C) content ranges from 173 to 906 g/kg^1, phosphorus (P) content ranges from 3 to 480 g/kg^1, nitrogen (N) content ranges from 2 to 56 g/kg^1, and potassium (K) content ranges from 1 to 58 g/kg^1 [16]. Biochar was shown to have densities ranging from 0.25 to 0.75 g cm^{-3} depending on the kind of wood utilized [17]. The density changes are caused by the wide range of biomass feedstock and pyrolysis conditions.

Biochar, depending on its specific composition, can have a considerable influence on a variety of soil parameters [18]. The appropriate biochar application rate is yet unclear since it differs according to the biochar type, soil type, and species being farmed. Plant growth responses have been positive between 0.5 and 135 t ha^{-1} of treatment [19]. Overall, biochar improves soil electrical conductivity and cation exchange capacity [20, 21]. Furthermore, its basic character may help in lowering soil acidity, which is beneficial to crop production [22], hence increasing crop output [23].

As biochar is porous and can store air and water, it can improve soil aggregation by increasing porosity while lowering bulk density and tensile strength [24]. Biochar addition affects soil water retention [25], soil biota composition and plant rooting pattern. This is due to the fact that lower tensile strength promotes root movement through the soil, resulting in root proliferation and elongation [26]. It also helps invertebrates to move in the soil, making root predation simpler because sand absorbs and discharges water fast, boosting the soil's capacity to retain water [25, 27]. According to a study [28], biochar macro-pores have been found to protect a wide range of microorganisms against drying out and predation by bigger soil species [28, 29].

Nitrogen (N), potassium (K), and phosphorus (P) levels in soil can be increased by using biochar [72]. As a result, biochar additives to soil can increase N and P cycling as well as C sequestration. Because of its remarkable nutrient-adsorption ability, biochar may collect and retain both naturally occurring and fertilizer-added nutrients in the soil, limiting their loss [73]. For example, improving radish crop dry matter production by mixing biochar with N fertilizers boosted both accessible soil N and N in the crops themselves [74]. This adsorption capability may have ramifications for heavy metal toxicity and mobility. Biochar made from dairy manure was shown to be efficient in immobilizing atrazine and lead (Pb) [75] when applied to soil and water [76]. Because biochar application lowered the availability of lead (Pb), chromium (Cr), copper (Cu), and zinc (Zn), there was less likelihood of heavy metal contamination of groundwater [20, 21, 77, 78]. Because of biochar's ability to bind to and store harmful substances, it may help to minimize pesticide and herbicide accumulation in crops [79].

Studies using crops such as wheat, maize, and tomatoes suggest that improving the above soil conditions can result in increased plant growth and yield [80, 81]. Soil supplemented with varied temperatures of bamboo biochar resulted in enhanced growth of the plant and higher quality tomato fruit [82]. Biochar improves crop growth, quality, and production, especially in areas prone to drought and salt stress [83, 84].

PLANT-BIOTIC INTERACTIONS WITH BIOCHAR

Uses of Biochar

According to a study [85], the inverted U-shaped dose-response curve revealed in plant pathogen investigations that biochar is helpful at low concentrations (1%) but generally useless at higher concentrations (>3%) [37]. As a result, biochar manufacturers should think about how biochar affects plant diseases and standardize the feedstocks and concentrations they employ for agricultural applications [38]. Biochars can be used in this process to create reliable and reproducible results for farmers. This is a significant consideration since the effect of biochar on lowering plant disease in agricultural systems varies greatly depending on the origin and technique of processing of the raw material.

Biochar can protect plants against diseases in a variety of ways. Biochar has been used efficiently to combat several airborne and soil-borne pests and plant diseases Table **1**. It has been established that biochar water-wash extracts have growth-promoting effects owing to the abundance of organic and inorganic components they contain [86]. This strategy is intriguing, and additional research is certainly required.

CHAPTER 5

Impact of Biochar on Crop Yield and Production

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Abstract: Urbanization and population growth have significantly impacted the health and fertility of the soil, putting more strain on farming systems. It is becoming increasingly necessary to use chemical pesticides and fertilizers in order to meet the world's growing food demand. There is a significant contribution to greenhouse gas emissions from these practices. The use of biochar as a multifunctional carbon material is being extensively investigated in order to address the problems of improving soil fertility and lowering climate change at the same time. In order to enhance seed germination and seedling growth, biochar is applied at a low level. In addition to changing the abiotic and microbial activities of the rhizosphere, biochar increase the mineralization of nutrients and make them more available to plants. By reducing heavy metals and increasing plant resistance to environmental stresses, biochar increases plant resistance to pathogens and abiotic challenges. By providing an in-depth analysis of biochar's impacts on crop physio-morphological traits, soil's physio-chemical properties and productivity, as well as ways toreduce environmental problems were determined. As a result of this chapter, biochar can be produced in a way that is efficient and serves the purpose that crops and soil need. Increasing crop production, assuring food security, and improving environmental management may all benefit from it.

Keywords: Agricultural production, Biochar, Carbon substance, Crop yield and food security, Growth and development, Plant resilience, Soil fertility, Urbanisation.

INTRODUCTION

Global food security is seriously threatened by soil degradation brought on by intensive farming methods and shifting climate patterns [1]. The environment and sustainable agricultural practices are also harmed by the exponentially rising greenhouse gas (GHG) emissions caused by a variety of human activities [2]. The

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world's agricultural sector will be under tremendous strain as a result of the expanding population, which is projected to reach 9.8 billion by the year 2050 [3]. So, to feed the growing populace, satisfy the rising food requirement, and mitigate the effects of changing climate, cost-effective, basic techniques that can enhance soil health, increase field crop production, and assure a renewable agricultural system and environment are needed [4]. According to Tillman *et al*. [5], agriculture is a significant cause of climate change and is expected to get worse if it is expanded or intensified. According to Foley *et al*. [6], a number of management and policy options are being researched and discussed, including improving resource use efficiency, promoting "sensible diets," lowering food waste, using advanced crop varieties, including genetically modified crops, and bridging "yield gaps" on underperforming lands. The application of innovative strategies that can generate better yields with little to no environmental harm is vitally needed, given the magnitude of the issue and the difficulties in putting most of the choices outlined into practice.

A carbonaceous substance called biochar is created when different feedstocks are broken down using various pyrolysis processes in a limited oxygen supply environment [7] (Fig. **1**). The addition of biochar has a wide range of beneficial effects, including better soil nutrient availability [8], increased soil microbial activity and improved soil nutrient absorption by plants. [9]

Biochar is a potential substance for managing soil, enhancing soil fertility, lowering greenhouse gas emissions, and managing the environment due to its distinctive properties, including strong adsorption capacity, micronutrient, improved cation exchange capacity (CEC), high permeability and more surface functional groups such as phenolic or inorganic molecule unit [10, 11]. The most often reported benefits of applying biochar to crops are higher agricultural yield and production, which is congruent with the idea that it will affect the net greenhouse gas balance positively [12, 13].

There is evidence that adding biochar to soils can increase yields by over 300 percent in some circumstances [14]. Nevertheless, a thorough examination of the published literature reveals that such significant increases in yield are further a deviation from the norm, and a variety of crop production reactions, including adverse ones in some circumstances, have been recorded [12].

This significant heterogeneity emphasizes the need for a mechanistic understanding of the biochar application impact on crop yields in order to enable reliable forecasts of the effects that are most likely to occur.

Also, to enable the effective formulation of policy to guide recommendations for its future usage, it is vital to highlight present gaps in our knowledge of biochar's potential effects on agricultural output (and other ecosystem services), both positive and negative. Moreover [15], research reported improvement in soil properties such as bulk density, infiltration rate, water holding capacity, hydraulic conductivity, aeration of the soil, pore spaces, bulk density, soil infiltration level, stability of soil aggregation, and decreased bioavailability of heavy metals to plants grown in unfriendly or poorly structural soils by stabilizing them. Moreover, biochar encourages microbial abundance and lessens the impacts of heat, drought, and salt on crops [16]. It promotes carbon sequestration, boosts biological nitrogen fixing in legume crops [17], and improves crop growth and production [18]. The kind of biochar used, the temperature at which it is made, the quantity of biochar used, and the soil type all have a significant role in the above-mentioned results.

Before a detailed strategy can be created and biochar may be used in agriculture, it must exhibit direct and/or indirect advantages on certain crucial soil qualities without degrading the others. Therefore, verification of how biochar affects crop yields would show whether it has the potential to help or hinder efforts to achieve global food security while also assisting in the mitigation of climate change.

Role of Biochar on Plant Physio-Morphological Attributes

Many scientists have worked on the effect of biochar application on plant physio-morphological characteristics and concluded that due to variables like the biochar and soil type, several physiological features either respond to the addition of biochar or they do not [19]. In this section, we will discuss various studies by scientists on the application of biochar to plant physiological attributes. For instance, adding biochar to the soil reduced the amount of chlorophyll in the leaves of rice plants grown on subpar soil [20]. Previous studies reported that improvements in anthocyanin (60%), carotenoids, protein content, lycopene, chlorophyll and stomatal CO_2were 60%. 29%, 20%, 30%, 40% and 22%, respectively. They also noted improvements in transpiration and photosynthetic rate *i.e.*, 42% and 45%, respectively. When the application rate of cotton biochar increased from 3% to 5%, sugars and amino acids were reduced. Mau and Utami [21] reported that increased phosphorus availability, absorption, and corn growth were also improved with the use of biochar. After adding biochar to the soil at a rate of 3 kg m^{-2}, the jute plant's chlorophyll levels, photosynthetic rate, and stomatal conductance were all found to be higher than that in the control [22]. According to Haider *et al*. [23], arid sandy soils boosted crop growth by boosting photosynthetic rates and the relationship between plants and soil water under biochar application in both dry and wet circumstances. Physiological indices in maize and wheat cultivated on loamy soil were favourably impacted by biochar. However, 5% biochar treatment had a more favourable effect than the control on

CHAPTER 6

Environmental Implications of Biochar

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Abstract: Biochar is a form of charcoal that is produced by heating organic material in the absence of oxygen. It has been studied as a potential tool for mitigating climate change by sequestering carbon in the soil, improving soil fertility, and reducing greenhouse gas emissions from agriculture. However, the environmental implications of biochar production and use are complex and depend on various factors, such as the feedstock used, the production process, and the intended use. One potential benefit of biochar is its ability to sequester carbon in the soil for long periods, potentially reducing greenhouse gas emissions. However, the amount of carbon sequestered and the duration of sequestration may vary depending on factors such as soil type, climate, and management practices. Additionally, there is a risk of releasing greenhouse gases during production, particularly if the feedstock is not properly managed. It can also improve soil fertility by increasing nutrient retention and reducing nutrient leaching. However, the effectiveness of biochar for this purpose may depend on factors such as soil type, climate, and the properties of the biochar itself. There is also a risk that the use of biochar could lead to soil acidification or other unintended consequences. The use of biochar in agriculture could also have implications for water resources. While biochar has the potential to reduce nutrient leaching, it could also increase runoff and erosion if not properly managed. Additionally, the production process could require significant amounts of water, particularly in areas where water resources are already limited. Overall, the environmental implications of biochar depend on various factors and require careful consideration. While biochar has the potential to provide a range of environmental benefits, it is important to ensure that its production and use are sustainable and do not lead to unintended consequences.

Keywords: Climate change, Greenhouse gas emission, Heavy metal, Soil remediation.

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INTRODUCTION

For sustainable environmental applications, the use of biochar as an amendment is a catalyst for recent global enthusiasm [1]. A practical solution to the anticipated issues in the agronomic and ecological sectors is to employ biochar as a specially formulated amendment [2]. Due to the presence of aromatic carbon, biochar is more resistant to microbial breakdown than regular (uncharred) organic matter [3]. Biochar persists in the soil from 1000 to 10,000 years and increases soil carbon stock due to its recalcitrant properties [4]. A recent method for cleaning up soil contaminated with heavy metals is the use of biochar as it has more surface area and a porous structure [5]. Here, a summary of using biochar to remove heavy metals, reduce greenhouse gas emissions, and slow down climate change is given.

Removal of Heavy Metals

Soil pollution by heavy metals (HMs) is a significant global problem that threatens sustainable development. Major sources of this heavy metal contamination are industrial operations like mining and smelting and agricultural activities [6]. Various *in-situ* and *ex-situ* techniques have been used to remediate HM-contaminated soils. Among these techniques, *in-situ* HM immobilization using biological waste has become well-established owing to its efficiency, economic feasibility, and ease of adaptation. Biochar application to contaminated soil is considered a promising method for HM immobilization because biochar can adsorb and immobilize HMs as its surface area, microporosity, surface functional groups, pH, and cation exchange capacity are superior to those of raw feedstock [7]. In order to immobilise HMs (and metalloids) such as As, Cd, Cu, Pb, Cr, Ni, Co, and Zn in soils, a variety of biochar is produced from various feedstocks (such as sewage sludge, manure, and crop residue) under various production conditions (such as slow pyrolysis, fast pyrolysis, gasification, and hydrothermal carbonization) [8]. The effect of biochar from various feedstocks on HM is shown in Table **1**.

Table 1. Effect of various biochar on heavy metal removal.

Biochar	Heavy Metal	Result	References
Hardwood biochar	Zn and Cd	Reduced their cytotoxicity	[9]
Chicken manure	Cu	Decreased exchangeable fractions of Cu	[10]
Mix of hardwoods	As, Cd, Zn	Leachate concentration of these metals decreased due to the sorption process	[11]
Eucalyptus	Cd	Cd bioavailability reduced	[12]
Rice Straw	Cu, Cd, Pb	Immobilization increased	[13]

(Table 1) cont.....

Biochar	Heavy Metal	Result	References
Chicken manure and Green waste	Cd, Pb	Immobilized the metals	[14]
Sugar cane, walnut wood chip	Hg	Enhanced adsorption	[15]

Charcoal contains some alkaline and alkaline earth metals and holds more OH^-, therefore, the inoculation of charcoal in soil enhances the efficiency of immobilizing the soil contaminated with heavy metals [9].

Biochar Mechanism for Metal Removal

Heavy metals are hard to biodegrade as compared to organic pollutants. Furthermore, biochar has a porous structure, greater surface area, and a lot of surface functional groups, and it can successfully repair HM pollution. The following are the main mechanisms of biochar absorption for heavy metals:

Ion Exchange

The basic principle behind this mechanism is the exchange of protons and ionized cations with dissolved salts on the surface of biochar. The surface functional group of biochar and the characteristics of the pollutant determine how well it may adsorb heavy metals [16]. Metal adsorption increases as biochar's cation exchange capacity increases. Ion exchange occurs when groupings of negative charges on the surface of biochar engage electrostatically with groups of positive charges in the soil. This type of reaction, which falls under nonspecific adsorption and has lower adsorption energy, is clearly reversible [17].

Precipitation

By adsorption and dissolution-precipitation of mineral constituents, biochar can effectively reduce the activities of heavy metals. It implicates the formation of mineral precipitates in the solution or on the surface of the sorbing material. The addition of biochar can raise the pH of the soil, and the precipitation of hydroxide, carbonate, or phosphate from the reaction of heavy metal ions with -OH, PO_4^{-3}, or CO_3^{-2} can solidify the heavy metal contaminants [18].

Complexation

This method of metal complexation involves the production of multi-atom arrangements through the interaction of unique metal ligands. Biochar binds HM comprising oxygen functional groups in their structure like hydroxyl (-OH) and carboxyl (-COOH). This oxygen content may boost the biochar's surface oxidation, which would then enhance metal complexation [19].

CHAPTER 7

Potential Limitations of Biochar

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Abstract: Agriculture nowadays confronts several challenges due to the increase in global food demand and environmental concerns. In recent years, there has been a significant increase in the application of biochar in agricultural soils. Biochar has been shown to have various benefits in enhancing soil quality and crop yield. Biochar can be used to boost up the soil carbon pool, as an adsorbent to clean up soil contamination and to decrease greenhouse gas (GHG) emissions. The fate of biochar in agricultural soils has been found to depend on a few factors, including pyrolysis temperature, feedstock, soil type, and biotic interactions. Biochar in freshwater systems and as a source of black carbon emissions, however, calls for more research because they can have detrimental effects on the climate and can also cause toxicity. Several techniques used by biochar systems (such as surface albedo, black carbon emissions from soils, *etc.*) or nutrient leakage into water bodies can also have adverse impacts on the climate. Environmental assessment studies sometimes overlook these elements due to the complexity of the implications. Specific emission factors derived from diverse climate and ecosystem models are essential for improving the characterization of the heterogeneity of varying local conditions and combinations of feedstock, pyrolysis processes, soil conditions, and application practices. These factors can help improve the resolution and accuracy of environmental sustainability analysis of biochar systems. Moreover, the use of biochar has been shown to be harmful in several circumstances, directly or indirectly deteriorating the agricultural soils and our environment. Moreover, the variability in feedstock costs can pose challenges to the economic viability of large-scale biochar production. Government policies and incentives that support sustainable feedstock management and biochar production can play a significant role in overcoming this hurdle and promoting the broader use of biochar for its environmental and agricultural benefits. This chapter evaluates the limitations associated with biochar production and its application in agricultural soils and the environment.

Keywords: Albedo effect, Biochar limitations, Negative yield response, PAHs.

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INTRODUCTION

In recent years, biochar has emerged as a beneficial approach [1] that can function as a carbon sink as well as an amendment that enhances soil quality, and increases fertility, and water-holding capacity, simultaneously reducing the risk of land degradation [2]. When biomass is thermally decomposed, it produces three by-products: biochar (a solid), bio-oil (a liquid), and syngas [3]. Pyrolysis is the thermal breakdown of biomass at high temperatures and under conditions of either very little oxygen or lack of oxygen (gas) [4].

Various complex interactions between the pyrolysis of biochar and its application to agricultural soils affect the ecosystem and climate. The pyrolysis process used to produce biochar emits different gases, while biochar application alters the balance of soil emissions (*e.g.*, N_2O, CH_4, NH_3, and NOx) [5]. Complex mechanisms, such as the long-term biogenic carbon storage in soils and altering soil reflectivity (such as albedo) by darkening the surface, are other ways in which biochar affects the climate system [6]. All these factors are important for assessing environmental issues, including eutrophication, acidification, and human health concerns [7].

A growing number of studies evaluate the potential for technical, economic, and sustainable deployment of biochar on a large scale as a method to reduce emissions [6]. Individual studies focus on different pyrolysis systems and one or more environmental implications, such as stability, impacts on soil organic carbon (SOC) over time [8], impacts on soil physical and hydraulic properties, soil degradation, agricultural yield [9], greenhouse gas balance (GHG), nitrogen availability and emissions [10], phosphorus run-off, as well as potential toxicity and impacts of biochar on pesticides [11]. Depending on the supply of feedstock, the cost of producing biochar may change, which is also a hindrance in the commercial application of biochar [12].

Agricultural Soils

Although most of the publications show the advantages of biochar application, there are certain limitations associated with the application of biochar. For instance, soil's aging ability is inhibited by biochar, and intermittent additions of fresh biomass may be necessary for optimum nutrient cycling and soil-water conditions. Anyanwu *et al*. (2018) demonstrated that biochar that has been aged in soil has a deleterious impact on the development of earthworms and/or fungi [13]. Moreover, *Oryza sativa* and *Solanum lycopersicum's* subsurface root biomass was found to be decreased because of the aged biochar. It has been demonstrated that biochar has low thermal diffusivity, which reflects a reduction in soil thermal diffusivity [14].

Soil-Specific Effects

Contrary to what is commonly believed, biochar has also been shown to have benefits that are soil specific. Hence, not all soil types may benefit from biochar addition in the same way [15]. It is important to highlight that the biochar studies were conducted in areas with temperate soils. Hence, our understanding of its consequences on the boreal environment is still limited [13]. Moreover, many studies have observed weed problems after using biochar. Safaei Khorram *et al*. (2018) claim that applying biochar frequently may not be the best weed management strategy because it causes a 200% increase in weed growth during lentil cultivation when applied at a comparatively high rate of 15 t ha^{-1} [16]. Vaccari *et al*. (2015) predicted that different plant species and plant parts showed different productivity after biochar application. They demonstrated that applying biochar at the rate of 14 t ha^{-1} to tomato plants enhanced their vegetative growth but not the fruit yield [17]. Additionally, the use of biochar can prevent plants from flowering as soon as they would otherwise. High-temperature biochar typically contains more ash than biochar generated at low temperatures [8]. Hence, it was thought that plants cultivated in soil amended with biochar generated at high temperatures might have negative effects. The ability of biochar to adsorb nitrogen as well as necessary elements like Fe, which can be detrimental to plant growth, is another potential drawback of biochar amendment [18]. Moreover, biochar may interact with soil nutrients and act as a competitor for nutrients, thereby reducing the availability of nutrients to plants [19]. For instance, the precipitation/sorption processes of phosphate may be aided by the application of biochar and phosphorous fertilizer in saline-sodic soil. This interaction may ultimately result in the plants' access to phosphorus being reduced [20]. When it comes to the biological effects of adding biochar to soil, it can impede the decomposition of organic matter, which correspondingly lowers the abundance of fungal species, such as Ascomycota and Basidiomycota by 11 and 66%, respectively [21]. Hence, it is crucial to examine feedstock properties. Gonzaga *et al*. (2018) found that where coconut husk biochar added to soil at a rate of 30 t ha^{-1} improved 90% of the Zea mays biomass, orange bagasse biochar applied at a similar rate had no visible effect [22]. It was established that the contaminated feedstock can deteriorate plant development [23].

It is reported that alkaline soil conditions typically result in negative yield responses [24] (potentially restricting P supply to plants). When biochar is applied at rates between 50 and 150 t per hectare in tropical soils, yield responses improve, but rates over 50 t have statistically significant negative effects on yields in temperate soils [24].

CHAPTER 8

Future Perspectives

Biochar is typically produced through the pyrolysis of organic material, which can emit greenhouse gases and air pollutants if not properly managed. Additionally, the raw material used for biochar production may come from unsustainable sources, such as logged-over forests. To overcome these concerns, future research should develop sustainable biochar production methods that minimize environmental impact, which may involve the use of waste or agricultural residues as feedstock, which would reduce the need for the use of new land, and potentially reduce greenhouse gas emissions. Renewable energy sources for pyrolysis and deploying carbon capture and storage technology to reduce greenhouse gas emissions are two most potential techniques for sustainable biochar production. Furthermore, localized biochar production plants can cut transportation costs while also promoting local economic growth.

Beyond agricultural applications, biochar has shown potential as a material for environmental rehabilitation. Biochar can effectively adsorb pollutants and toxins from water and air due to its high surface area and porous nature. Biochar has been shown in studies to be useful in applications such as water filtration, wastewater treatment, and air purification. Furthermore, the creation of biochar from waste materials can provide a long-term waste management and environmental remediation option. Extending biochar use beyond agriculture has the potential to provide considerable environmental advantages, promoting the transition to a circular economy.

Biochar is a promising tool for environmental protection and sustainable agriculture. However, in order to fully exploit its potential, academics, farmers, and policymakers must work together. This partnership may result in the discovery of the most effective and practical use of biochar in agriculture, as well as the development of policies and incentives to encourage its usage. Researchers can conduct real-world studies on various biochar application methods and feedstocks, and farmers can provide feedback on practicality and economic viability. Policymakers may fund research and development, offer incentives to farmers to use biochar and implement rules to ensure its safe and sustainable usage. Collaboration may also lead to the discovery of novel applications of biochar that are not related to agriculture, such as environmental remediation or renewable energy production. Overall, stakeholder engagement can optimize biochar's potential for sustainable agriculture and environmental protection, contributing to a more resilient and environmentally friendly future.

Policy and incentive development to encourage the use of biochar in agriculture could play an essential role in improving sustainable agricultural practices. Governments could implement rules that provide financial incentives or tax advantages to farmers who use biochar. Policies might also be devised to encourage the use of biochar in specific regions or crops depending on its potential benefits. Research on biochar efficacy in various soil types and crops could serve to inform policy decisions and encourage the use of biochar as a sustainable agricultural practice. Governments should also invest in research to produce more sustainable and cost-effective biochar production technologies.

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