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Biochar: A Comprehensive Review on a Natural Approach to Plant Disease Management

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Abstract

Since time immemorial organic amendments have been an important strategy for improving soil fertility and suppressing a wide range of soil-borne pathogens. Biochar, a charcoal-like amendment has true potential in managing phytopathogens with an eco-friendly approach. It is produced by subjecting plant materials and agricultural waste to high temperatures of around 900°C in limited oxygen conditions. Biochar is considered to be an excellent carbon sequester and has an undeniably imperative role in improving soil properties. Biochar has innumerable applications in the remediation of environmental pollutants by immobilizing heavy metals such as Cadmium and Arsenic and degradation of dyes and pesticides. One of the most significant advantages of biochar in addition to mitigating environmental pollution is effectively managing plant pathogens by altering soil physical and chemical properties and promoting antagonistic microorganisms. Biochar directly suppresses plant pathogens by priming plant defense mechanisms. For instance, sugarcane bagasse biochar remediates Cd from contaminated soil, and citrus wood biochar induces systemic resistance against *Botrytis cinerea* in host-*Lycopersicon esculentum, Capsicum annuum* L. cv. Maccabi and *Fragaria ananassa.* Nevertheless, it is essential to acknowledge its limitations, such as the potential to absorb and enhance the residual activity of harmful chemicals. Further research is needed to develop a deeper understanding of biochar's properties and mechanisms for more effective results. Advanced techniques like meta-transcriptomics and metaproteomics hold the potential to provide invaluable insights into this field. The review provides a comprehensive overview of current information regarding biochar, covering its production techniques and highlighting its agricultural benefits, with a particular focus on its role in plant disease management. Furthermore, the associated risks and concerns are also discussed.

Keywords: Biochar, Agri-chemicals, Eco-friendly, Phyto-pathogens, Disease, Management

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INTRODUCTION

The dramatic increase in the global population is the prime concern that resulted in major risks to food security and climate change. The global population continues to grow, with recent estimates projecting a range of 9.4 to 10.1 billion people by 2050.[1] Currently, the availability of agricultural land is limited, and the most sustainable approach to address future food shortages is by increasing food productivity within these constraints.[2] The primary factors contributing to reduced crop yields can be categorized into biotic factors (such as pests, pathogens, herbivores, etc.) and abiotic factors (including salinity, alkalinity, chilling injuries, etc.). Estimates show that plant pathogens cause 26% yield loss while 10-20% of them are only by soil-borne pathogens.[3,4] Traditional agriculture system follows the use of agrochemicals, soil disinfection, resistant varieties, etc. for pest management. Among these, pesticides present significant environmental risks as they harm beneficial soil microbes, poison aquatic ecosystems, and contribute to biomagnification in the food web by contaminating water and soil.[5,6] However, there is a constant endeavour to promote long-run sustainable organic agriculture as an alternative to conventional agriculture systems.

Biochar, a solid byproduct created through the pyrolysis of organic materials, holds the potential to effectively suppress disease-causing pathogens such as fungi, bacteria, nematodes, and insect pests besides its numerous beneficial effects and ability to amend soil quality in conjunction with sequestering carbon.[7] Biochar is a charcoal-like product derived through the thermochemical conversion of plant and animal biomass under controlled, low-oxygen conditions.[8,9] The potential of biochar has been recognized throughout human history. It is an economically viable method with positive environmental implications, offering significant benefits for carbon storage. Produced through the exothermic and carbon-negative process of pyrolysis, biochar is energy-efficient and also yields valuable byproducts like liquid bio-oil and syngas, contributing to bioenergy production.

Biochar stands as a promising resource for enhancing and safeguarding crops, thanks to its numerous benefits. The Amazon regions, in particular, are abundant in black carbon, known as Terra Preta. Terra Preta soil is enriched with carbon, nitrogen, phosphorus, potassium, and magnesium, offering fertile ground for agricultural productivity.[10] There are several methods (pyrolysis, torrefaction, gasification, flash carbonization, and hydrothermal carbonization) exploited for the production of biochar, among which pyrolysis is the most preferred one.

Recently, numerous studies have highlighted the advantages of using biochar. A detailed review of biochar application's benefits is given by Kamali *et al.*[11] Sugarcane bagasse biochar (SBB) has been used to reduce the ill effects of polystyrene microplastic in the rice ecosystem by reducing methane emissions and improving yield and biomass.[12] Similarly, SBB has been also used to improve corn and rice growth in the lead and cadmium-contaminated soil. The biochar significantly improved shoot and root dry weight emphasizing SBB as a suitable remedy in contaminated soils.[13,14] Its high porosity has been observed to create a microorganism-friendly environment.[10] Furthermore, it exerts an impact on community structure and function, leading to a shift in microbial communities that favor aromatic carbon sources. Broadly, five mechanisms have been suggested to support the disease-suppressive effects of biochar. These include the activation of systemic resistance, alteration of soil physicochemical properties, augmentation of beneficial rhizospheric microorganism populations, and the secretion of fungitoxic, phytotoxic, or allelopathic compounds, either directly or indirectly.[15,16] In addition, it was observed that both systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways play a role in the disease suppression mechanism.[17] In the last two decades, numerous papers have been published, emphasizing its importance in alleviating biotic stress and improving soil health. This review paper aims to provide a comprehensive and current overview of biochar's role in promoting sustainable agriculture. It particularly emphasizes its contributions to soil health, disease management, and the mechanisms through which biochar enhances plant resistance and associated limitations to mitigate sustainable agriculture.

Biochar in Agriculture

Biochar has a profound application in agriculture because of its properties which have direct positive effects on soil, microbial consortium as well as on plants (Figure 1). Properties like porosity and ability to undergo natural oxidation leading to the generation of functional organic compounds make it a perfect candidate for water treatment, pesticide management, controlled release fertilizers, waste management, etc. Moreover, the presence of nutrient and nutrient retention capacity makes it an impeccable fertilizer. Through different mechanisms, it also protects the plants from various pathogens and other pests and also helps in environmental remediation.

For meaningful results, it's crucial to have a well-characterized biochar. Understanding its properties is not only essential for agriculture but also for carbon sequestration. The characteristics of biochar are significantly shaped by the pyrolysis process, encompassing various factors and the choice of feedstock. These factors include the heating rate, maximum temperature reached, duration of temperature exposure, pressure conditions during production, and post-pyrolysis treatment. Thus, deliberate control of these variables can enable the fine-tuning of biochar's specific properties. Physical characteristics of biochar are significantly influenced by temperature and the type of feedstock used. For example, biochar derived from rice and wheat exhibits higher bulk density compared to that from maize and pearl millet when prepared at 400°C. Additionally, it's well-established that subjecting biochar to low temperatures (400°C and below) yields biochar with a lower surface area (around 120 sq.m/gm) and reduced ash content. Conversely, employing higher temperatures (ranging from 600-900°C) typically results in biochar with a larger surface area (around 460 sq.m/gm) and higher ash content.[18]

The chemical properties of biochar are also temperature-dependent. Lower temperatures (400°C and below) produce biochar with lower carbon content, increased nitrogen, sulfur, potassium, and phosphorous levels, lower pH,

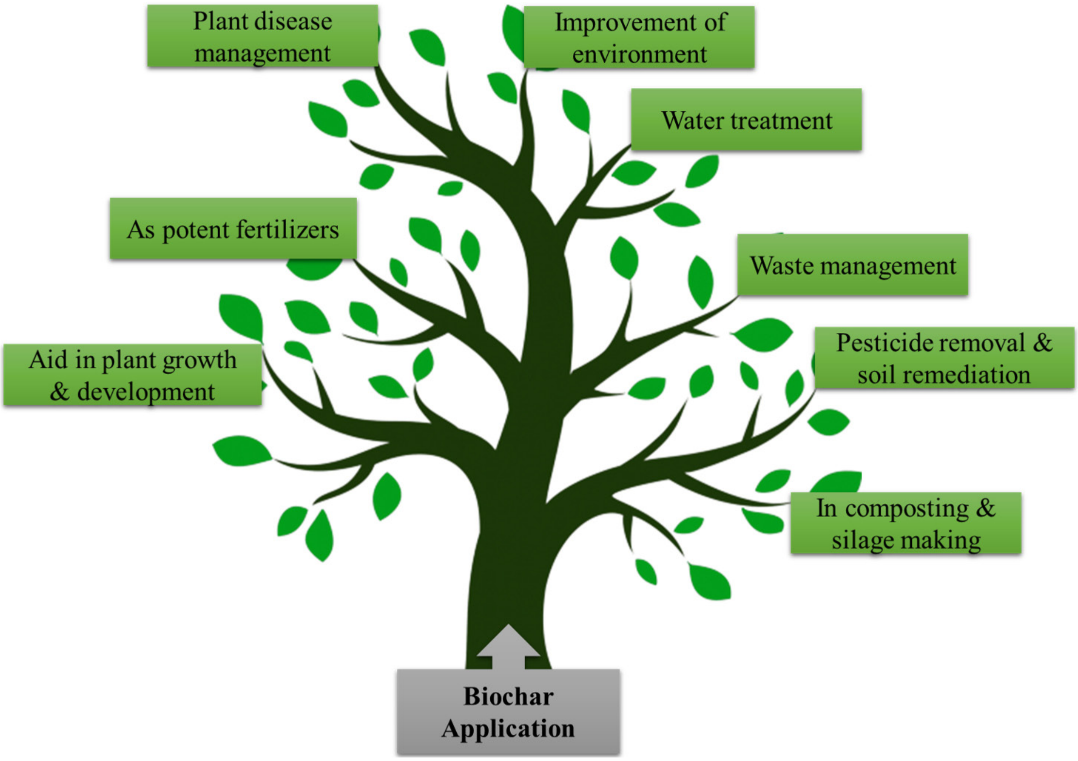

Figure 1. The wide range of applications of biochar in Agriculture

electrical conductivity (EC), and higher levels of extractable NO^{3-}. It also results in higher extractable phosphorous, NH^{4+}, and phenols. In contrast, higher temperatures (600-900°C) yield biochar with higher carbon content, lower nitrogen, sulfur, phosphorous, and potassium levels, higher pH, electrical conductivity (EC), and increased levels of extractable NO^{3-}, but lower extractable P, NH^{4+}, and phenols. Furthermore, the choice of raw materials also plays a role in determining the final chemical characteristics of biochar. For instance, biochar derived from rice residues exhibits the highest Cationic Exchange Capacity (CEC).[18]

Positive impact of biochar in agriculture

While several options for plant disease management are available, conventional chemical methods remain the most widely utilized. However, the use of chemicals in plant disease management comes with numerous drawbacks that cannot be overlooked. Pesticide application results in the presence of harmful chemical residues in the environment. Their excessive and inappropriate use contributes to the development of pesticide resistance in pathogens.[19] Equally significant is the fact that the use of chemicals has caused a reduction in the population of natural pest antagonists. Furthermore, these toxic substances pose severe health risks to farmers. Reports have highlighted the detrimental effects of these chemicals on the populations of honey bees, birds, and fish.[20] Additionally, there are alarming reports of groundwater contamination due to chemical runoff.

In agriculture, the utilization of biochar offers numerous benefits. Most significantly, biochar, as a soil amendment, plays a pivotal role in mitigating global climate change by significantly reducing greenhouse gas emissions. Due to its resistance to microbial degradation, it has a long-lasting impact on carbon sequestration.[21] The impact of differential rate of application of biochar on crop productivity was studied and the addition of biochar alone and supplemented with fertilizer led to a positive effect on crop productivity, indicating an average 10% increase in crop yields.[22] The positive effects of biochar on crop productivity can be attributed to four main mechanisms. The first is its liming effect, which

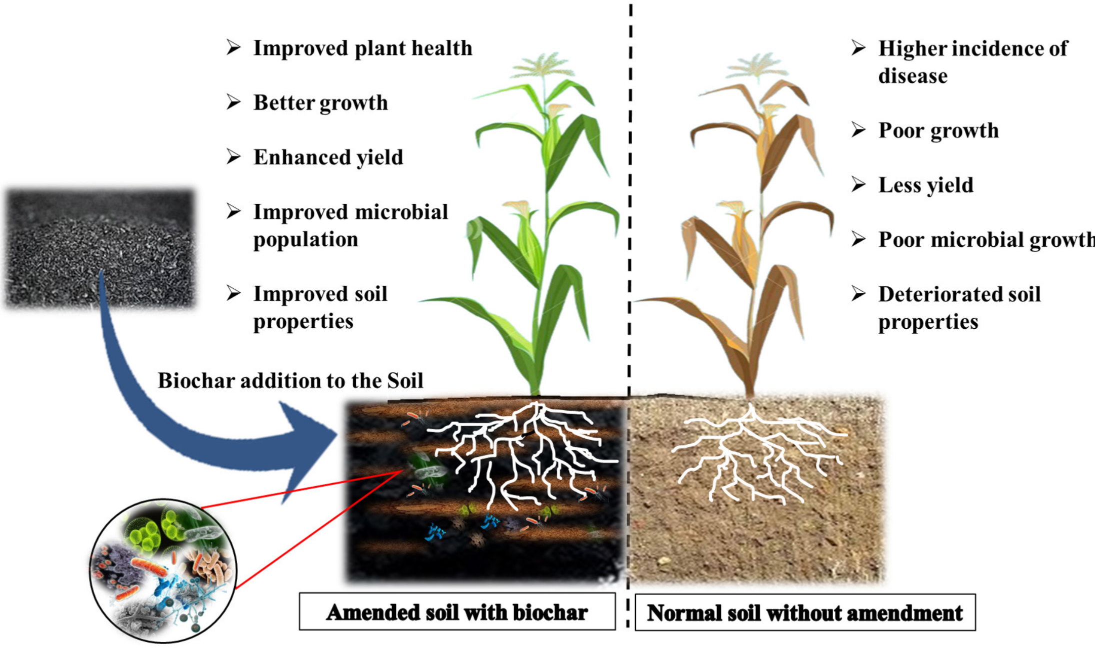

Figure 2. Comparative effect on soil physio-chemical and biological properties after amending with biochar

Table 1. Impact of biochar on the soil properties

Soil properties	Impact	Ref.
Cation exchange capacity	50% increase	39
Soil moisture retention	Upto 18% increase	40
Bulk density	Soil dependent	18
Fertilizer use efficiency	10-30% increase	41
Liming agent	1 unit pH increase	8
Biological fixation	50-72% increase	
Crop productivity	20-120% increase	
Mycorrhizal fungi	40% increase	42
GHG emission	highly reduced	8

raises soil pH and enhances crop growth. Second, its high water and nutrient retention capacity.[9] The third mechanism is linked to biochar's ability to adsorb and neutralize phytotoxic organic molecules and natural allelopathic compounds. The fourth mechanism involves biochar's capacity to promote the growth of beneficial microbes, which subsequently enhances plant growth and health.[23] In addition to its favourable impact on soil's physical and chemical properties, biochar also plays a crucial role in plant disease management by inducing systemic defence response in plants and indirectly by enhancing soil properties and antagonistic microbial load[24] (Figure 2).

Impact of biochar on soil chemical characteristics

The use of biochar in agriculture is increasingly attracting attention due to its ability to improve essential soil chemical properties, including enhanced cation exchange capacity (CEC) and the capacity to counteract soil acidity.[25] The carboxyl functional group present on the surface of biochar acts as an amendment for alkalinity and high soil CEC. The alkalinity of biochar can be attributed to variations in alkaline ash composition, the choice of raw materials, and the pyrolysis temperature.[26,27] The cation release, resulting from the protonation of carboxyl groups on biochar surfaces and the dissolution of carbonates, was the predominant mechanism responsible for the increase in soil pH buffering capacity.[28] Biochar application enhances the levels of essential elements, such as NH^{4+} and Ca^{2+}, thus improving nutrient retention capacity in the soil.[29] It also reduced the loss of N, P and K by leaching and through nitrous oxide emission. The biochar made out of pepperwood and peanut hull could effectively reduce the total amount of nitrate, ammonium, and phosphate in the leachates by 34.0%, 34.7%, and 20.6%, respectively.[30] Moreover, it leads to a reduction in inorganic nitrogen and an increase in the availability of organic nitrogen in the soil. This, in turn, stimulates root activity, enabling the plants to absorb more nitrogen from their surroundings.[31] As there are fluctuations of various soil microbial populations, it directly or indirectly affects the nitrification and denitrification in soil.[32] The nitrogen, phosphorus, or potassium content also differs in biochar (may be high or low) depending on the raw material used and the pyrolysis method. For instance, biochar produced from sludge or manure contains fertilizing elements.[25] Interestingly, biochar is considered chemically recalcitrant, with positive results observed even after eight years of study. This long-lasting effect is attributed to its dense structure and the slow release of organic carbon into carbon dioxide.[33,34]

Impact of biochar on soil physical characteristics

Biochar is widely recognized as a potent soil amendment with multifaceted benefits. It plays a crucial role in pH regulation, soil density and thermal properties, plant growth enhancement, soil structure, and fertility improvement, increased nutrient availability, and enhanced water retention capacity.[35] The addition of biochar to soil leads to a reduction in bulk density, significantly increasing the soil's water-holding capacity (WHC). This effect is attributed to improved soil aeration and increased water infiltration, which result from the reduction in soil compaction.[36] The presence of larger pores is the main key agent for enhancing soil aggregation and soil water retention.[37] Additionally, the diameter of the biochar particles also has a fundamental role in water retention, runoff water management, water erosion, etc.[38] The water retention capacity of soil is influenced by various factors, including the raw material used for biochar production, the production temperature, and the specific type of soil in which the biochar is applied. Interestingly, the same biochar may exhibit less effectiveness in improving water retention when applied to clay soil, whereas it proves most effective when applied to sandy and loamy soils.[36] Thus, the direct and indirect effect or alteration of soil physical properties after the application of biochar is the main factor in determining the harmful and beneficial microorganism population in the rhizosphere region.[39,40] For example, in the case of diseases like Cassava black root rot caused by *Scytalidium lignicola*, soil bulk density, especially when it's high, can positively influence disease severity. Likewise, the clay content in soil can enhance the activity of antagonist microorganisms such as *Bacillus* sp. and *Pseudomonas* sp., leading to a reduction in the pathogen population.[41] Similarly, the application of biochar along with *Bacillus subtilis* has a synergistic effect to reduce the early blight of tomatoes caused by *Alternaria solani* by 55%.[42]

Consequently, the application of biochar results in changes to bulk density, increased porosity, adjustments in permanent wilting point and field capacity, and enhanced available water content. These alterations directly or indirectly boost the host plant's resistance against pathogens and enhance agriculture's resilience to drought conditions.[43] Research has provided evidence of reduced pathogen populations, such as *Fusarium* sp., following three years of continuous biochar application. Likewise, biochar produced from rice straw has demonstrated a reduction in the incidence and severity of tobacco bacterial wilt disease. This disease suppression is attributed to changes in bulk density and the promotion of a beneficial rhizosphere microbial community (Table 1).[44]

Impact of biochar on soil microbiota

The soil microbiota plays a crucial role in soil function and provides various ecosystem services.[45] Soil microbes perform array of soil function such as decomposition of organic matter, regulate nutrient cycling, alleviate plant disease, and increase plant productivity.[46] While biochar is resistant to microbial decay, some initial degradation can occur due to both chemical processes and microbial activity.[47] This degradation produces organic matter that serves as nutrients for beneficial microbes such as mycorrhizal fungi, bacteria, and actinomycetes.[48] This, in turn, leads to an increase in beneficial bacterial populations and a decrease in pathogenic fungal populations.[23,49] Biochar has the ability to shift the microbial community towards those microbes that prefer aromatic carbon sources. It can also influence the activity of soil enzymes by altering their interaction with soil organic matter. Factors such as the high porosity of biochar, soil pH, and the specific type of soil it's applied to can lead to minor changes in the microbial niche.[10] Biochar provides a habitat for microorganisms

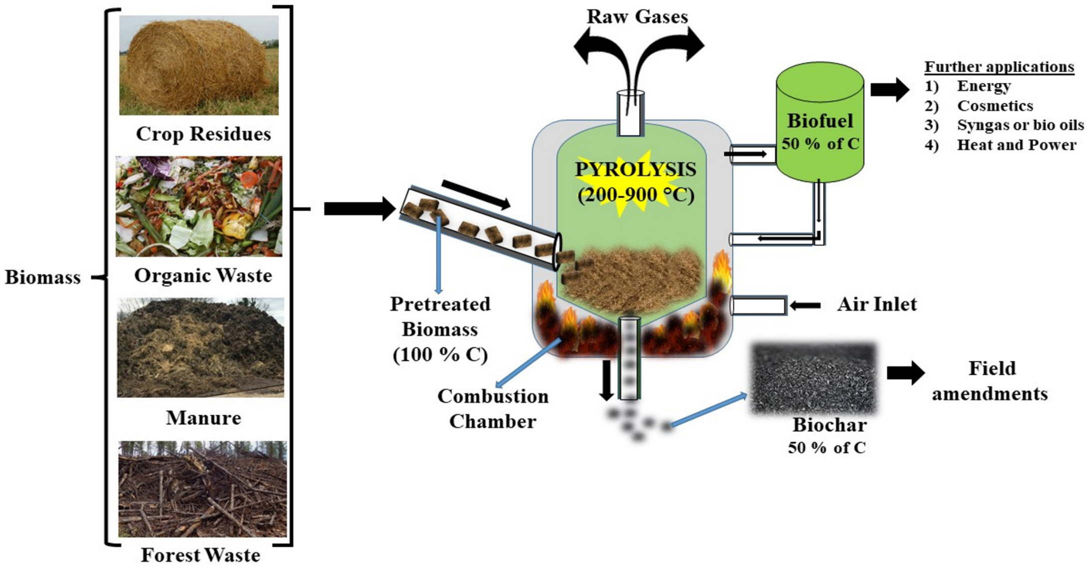

Figure 3. The production technique of biochar

Table 2. Reports supporting systemic induced resistance by biochar

Pathogen	Host plant	Biochar source	Ref.
Botrytis cinerea	*Lycopersicon esculentum*	Citrus wood	55
Botrytis cinerea	*Capsicum annuum* cv. Maccabi	Citrus wood	
Botrytis cinerea	*Fragaria ananassa*	Citrus wood – crop wastes	14
Botrytis cinerea	*Lycopersicon esculentum*	Greenhouse wastes	66
Colletotricum acutatum	*Fragaria ananassa*	Citrus wood – crop wastes	14
Leveillula taurica	*Capsicum annuum* cv. Maccabi	Citrus wood	55
Phytophthora cactorum	*Acer rubrum*	Wood (*Pinus taeda, P. palustris, P. echinata, P. elliotti*)	59
Phytophthora cinnamomi	*Quercus rubra*	--	

in its macropores, micropores, and mesopores, offering protection from predators. When biochar is applied, it enhances root growth and microbial development, leading to increased microbial reproduction, more efficient nutrient cycling, and enhanced enzymatic activity.[27,50]

The alteration of soil pH caused by the addition of biochar is a significant factor driving changes in microbial populations. This shift in pH influences nutrient availability, leading to the growth and proliferation of specific microbial groups, such as nitrifying bacteria and phosphorus-solubilizing bacteria, which play a crucial role in plant disease management. Studies have reported an increase in the population of Actinobacteria and the phylum Proteobacteria after the application of biochar.[51,52] The phylum Proteobacteria indirectly contributes to the management of plant pathogens by promoting the growth of antagonistic bacteria through the cycling of nitrogen, carbon, and sulfur.[53] Furthermore, it increases the population of nitrogen-fixing bacteria, such as *Azotobacter* sp. and *Azospirillum* sp., which enhance the formation of nitrogen-fixing root nodules, leading to a significant increase in biological nitrogen fixation in plants.[54] Application of biochar altered maize rhizosphere community predominantly to Proteobacteria (34.6%), Actinobacteria (24.7%), and Chloroflexi (14.4%). Actinomarnales were predominantly present in the rhizosphere and they attributed to plant height while Alphaproteobacteria had positive and negative impacts on N and K respectively.[55] Biochar application promotes the functional diversity of specific microbial communities, such as plant growth-promoting rhizobacteria (PGPR), which are capable of cycling soil organic matter and increasing its availability to host plants.[56] Biochar provides a favorable environment for PGPR growth and reproduction due to its porous nature, high surface area and ability to absorb nutrients.[57] PGPRs promote plant growth and alleviate pathogen stress by N fixation, P and K solubilization, production of growth hormones such as IAA and production of exopolysaccharide and lytic enzymes.[58]

One of the most studied antagonistic fungi, *Trichoderma* sp., employs various mechanisms for disease suppression, including competition, antibiosis, mycoparasitism, and the activation of systemic resistance in plants.[59] The addition of biochar to soil enhances the activity of *Trichoderma* sp., leading to a reduction in disease incidence. Minor alterations in soil enzymatic activity serve as sensitive indicators of changes in the soil ecosystem, and these enzymatic activities are linked to disease suppression. For instance, cassava black root rot has been associated with the enzyme urease and arylsulfatase.[59] On the other hand, studies have reported changes in soil microbiota due to biochar incorporation affecting mineral availability in the soil. The biochar application has reduced N mineralization due high absorption capacity for N compound leading to a shift in soil microbial communities. The application of biochar significantly disturbed the N oxidizer: N reducer ratio disturbing N availability in soil.[60] Adverse effects of biochar on soil invertebrates such as earthworms were reported. For example, decreased density of the earthworm including lower reproduction rate, slow growth and decreased burrowing activity was observed.[61]

Table 3. Studies supporting the enhanced abundance/activities of beneficial bacteria by biochar

Pathogen	Host plant	Biochar source	Ref.
Fusarium oxysporum f. sp. *asparagi*	*Asparagus* sp.	Coconut	57
Fusarium oxysporum f. sp. *radicis-lycopersici* and *Pythium aphanidermatum*	*Lycopersicon esculentum*	Pig bone	84
Fusarium oxysporum f. sp. *asparagi*	*Asparagus* sp.	Quest Biochar	85

The production technique of biochar

Several methods are being employed for the production of biochar *viz.,* pyrolysis (Figure 3) (such as fast pyrolysis, slow pyrolysis, flash pyrolysis, vacuum pyrolysis, hydro-pyrolysis, intermediate pyrolysis, and microwave-assisted pyrolysis), torrefaction, flash carbonization, hydrothermal carbonization, and gasification.[62] Biochar exhibits heterogeneity in its properties, which can be attributed to the diverse range of feedstocks and pyrolysis technologies employed. Common feedstocks for biochar production encompass switchgrass, pine woodchip,[63] peanut hulls,[64] corn hulls, pecan shells,[64] bark, rice, sugarcane, leaves,[65] paper sludge, cow manure, poultry litter,[63] sewage sludge, and aquaculture waste.[66] In addition to solid biochar, the bioenergy derived from the process can take the form of synthetic gas (syngas) or bio-oils, which have versatile applications such as heat and power generation. It is essential to monitor the storage conditions and any potential chemical or thermal activations during the production process, as these factors can significantly impact the surface chemistry of biochar.

Application methods of biochar

The application method and rate of application of any agricultural technology is crucial, and biochar can be applied using various established methods in agriculture. These methods include broadcasting, deep banding, spot placement, using tractor-propelled spreaders, and mixing with compost or manure. The application rate of 10-20t/ha significantly increased the photosynthetic rate by 25%.[67] While application of 50t/ha of biochar along with cattle manure increased maize yield by 46-58%.[68] Biochar's application positively influences the physical properties of soil, such as bulk density, particle size distribution, porosity, structure, and texture. The primary source and method of pyrolysis influence the physio-chemical properties of biochar. The biochar produced from seaweed, manure and crop residue has a higher pH and is rich in nutrition.[69] The application of biochar in soil significantly impacts its chemical properties. This includes an increase in soil carbon content, pH levels, and cation exchange capacity (CEC). Owing to its large surface area and porous structure, biochar helps in the retention of nutrients and water. With a density of 0.05-0.57kg/m^3 lower than mineral soil, biochar reduces the soil bulk density and facilitates nutrient release.[70] Moreover, biochar has been shown to reduce ammonia volatilization and enhance the immobilization of inorganic nitrogen, contributing to better nutrient management in soil.[71] Furthermore, biochar plays a crucial role in enhancing soil microbial communities and facilitating biogeochemical cycles. Through the formation of functional groups, biochar undergoes natural oxidation, creating sites that effectively retain nutrients and various organic compounds. In summary, biochar contributes to soil health by balancing pH levels, augmenting organic nutrient content, improving water-holding capacity, reinstating microbial communities, and reducing the presence of toxic pollutants, erosion, as well as the leaching and mobility of contaminants.

Status of biochar production in the world market

According to Transparency Market Research in 2017, the global biochar market is characterized by high competitiveness, featuring prominent players such as Full Circle Biochar, Genesis Industries, Cool Planet Energy Systems, Earth Systems Bioenergy, and Agri-Tech Producers. TRM reports that the global biochar market is poised for significant growth, with a projected compound annual growth rate (CAGR) of 14.5% during the forecast period spanning from 2017 to 2025. The biochar market is anticipated to grow from its initial value of US $444.2 thousand to a projected valuation of US $14,751.8 thousand by 2025. The annual biochar production in Europe was estimated to be 20,000 tons/year, while Norway alone produced 600 tons and is estimated to produce 1200 tons by 2024.[72] In the global biochar market, the type of feedstock used for biochar preparation is segmented into categories such as agricultural waste, animal manure, woody biomass, and more. The woody biomass segment is the dominant one, representing about 50% of the market share in terms of demand. Geographically, the global biochar market extends across regions including North America, Europe, Asia Pacific, Latin America, and the Middle East and Africa. Among these regions, North America holds the highest market share in both value and volume.[73]

Biochar as a potential weapon against pathogens

The first report of biochar's potential to protect against plant pathogens like mildew and rust dates back to 1847 when Allen first documented its use.[74] It has been well established that biochar can reduce disease incidence and severity significantly throughout the globe.[75] For instance, in the *Rosellinia necatrix- Persea americana* pathosystem, the addition of biochar significantly reduces both disease severity and incidence.[76] Additionally, numerous reports highlight the promising disease suppression capabilities of biochar against various pathogens, including *Ralstonia solanacearum* in tomatoes, *Rhizoctonia solani* in cucumbers, *Phytophthora cinnamomi,* and *Fusarium oxysporum* in asparagus.[77-80] The addition of biochar to soil induces changes in its physiochemical properties, ultimately promoting the growth of microbial communities. The increased microbial density of PGPR, *Bacillus* and *Lysobacter* have been reported to suppress disease caused by *Fusarium solani* were.[81] Biochar serves as a carbon source, which, in turn, fosters the development of lignin-degrading microorganisms. These microorganisms include fungal groups like *Dothydeomycetes* and bacterial groups like *Actinobacterials*. The decomposition by-products resulting from biochar amendments create a favourable environment for the development of bacterial groups, including gamma and beta-proteobacteria, which act as antagonists against fungi. Additionally, biochar application promotes the growth of other antagonist microbes in the soil, such as *Pseudomonas* sp., *Serratia* sp., and *Stenotrophomonas* sp. These microbes play a crucial role in suppressing fungal pathogens.[98]

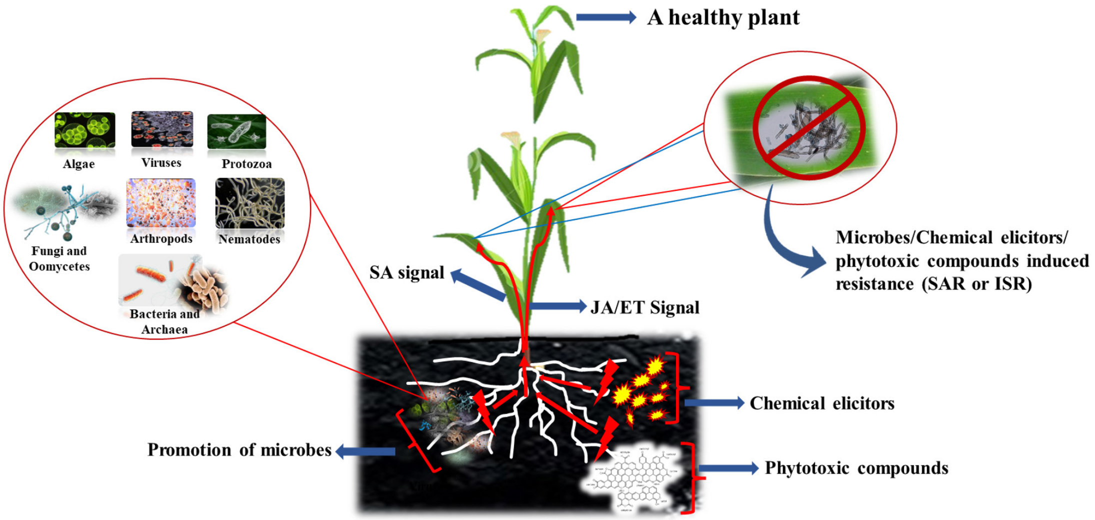

Figure 4. Possible Mechanism behind biochar mediated plant disease control

Araujo and his colleagues have reported a positive correlation between biochar and the biocontrol fungi *Trichoderma harzianum* in their effectiveness against *Macrophomina phaseolina.*[82] Amendment of biochar along with *Bacillus subtilis* reduced Fusarium wilt in radish.[83] The potential for disease suppression varies significantly, depending on the diversity of raw materials used, the production method, the application rate, and the type and properties of the soil.[84] Biochar produced from corn stover has been reported to effectively control root rot in soybeans caused by *Fusarium virguliforme*, while biochar derived from sawdust and poultry waste significantly reduces ear rot in maize caused by *Fusarium verticilloides.*[85,86]

Mechanism of plant disease control by application of biochar

While host plant disease resistance to a wide range of pathogens has been demonstrated with the application of biochar, the specific mechanisms underlying disease control are not yet fully understood. Disease suppression can result from both direct and indirect actions (Figure 4). The soil ecosystem and rhizosphere microbiota are closely related, and even slight alterations in soil characteristics can lead to modifications in rhizosphere microorganisms. It's worth noting that direct interactions of biochar with foliar pathogens are generally less significant compared to interactions with soil-borne pathogen.[87]

Induction of systemic plant defense

In the context of foliar diseases, biochar typically placed at a distance from the point of infection results in the induction of resistance, suggesting that biochar likely activates systemic resistance. Several factors could contribute to this activation, including the presence of chemical elicitors, phytotoxic compounds, and the promotion of beneficial microbes. Volatile organic compounds, minerals, and free radicals are among the major factors that induce systemic resistance in host plants. Additionally, both the systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways have been reported to be involved in this process[88] (Table 2).

Multiple studies have reported the induction of systemic resistance in host plants following the amendment of biochar. Evidence of reduced disease severity was observed in powdery mildew and gray mold-infected pepper and tomato plants, caused by *Leveillula taurica* and *Botrytis cinerea*, respectively, after the application of biochar and the activation of induced systemic resistance.[75] The molecular mechanism of biochar-induced systemic resistance in tomatoes was elucidated against Fusarium wilt. The biochar-induced priming effect on the plant and upregulated genes associated with jasmonic acid, cytokinin, auxin and phenylpropanoid pathway.[89] Similarly, the reduced foliar disease incidence in strawberry plants caused by *P. aphanis* and *B. cinerea* was observed after biochar amendment and it showed an activation of systemic resistance against the aforesaid pathogens.[17] Systemic resistance activation has also been observed against various pathogens, including *F. oxysporum* f. sp. *lycopersici* in tomato plants, *R. solani* in cucumbers, and *F. solani* in lupins, after the application of biochar.[80,90,91] When a pathogen attacks a host plant amended with biochar, it triggers a rapid increase in lipid peroxidation and superoxide production. These processes collectively have a positive impact on free radicals and the polyunsaturated fatty acid components, leading to disease suppression through systemic resistance.[92,93]

Inhibition of growth and development of pathogens

The pyrolysis of biomass brings about a significant chemical transformation, leading to the breakdown of O-alkyl carbons, which are associated with carbohydrates, and the simultaneous formation of aliphatic and aromatic carbon compounds.[94] Additionally, this process can generate organic compounds that exhibit strong fungitoxic properties. The resultant biochar was composed of a total of 29 predominant compounds, which include fatty acids, dicarboxylic acids, carboxylic acid derivatives, phenolic compounds, and tri-terpene acids. However, it's important to note that the direct toxicity of biochar towards pathogens is unlikely to be the sole explanation for the observed disease suppression. Other mechanisms and factors are likely at play in this process.[95]

Biochar exhibits a significant increase in surface area compared to the initial biomass used for its production. Its surface area can range from 0.5 to 450 m^2 g/L.[96] Biochar's sorption ability plays a significant role in its direct and indirect beneficial functions. This ability allows biochar to adsorb and retain various substances, such as nutrients and contaminants, in the soil. As a result, it can enhance soil fertility, reduce nutrient leaching, and immobilize toxic pollutants hence protecting the plant root. Additionally, the sorption capacity of biochar may indirectly influence the microbial community in the soil, promoting the growth of beneficial microorganisms and enhancing their activity, which further contributes to improved soil health and plant health and growth.

The presence of biochar in the soil has been observed to enhance the growth and colonization of arbuscular mycorrhizal (AM) fungi. This suggests that biochar may play a protective role for both plants and AM fungi by mitigating the effects of phytotoxic and fungitoxic phenolic compounds like cinnamic, coumaric, and ferulic acids. This positive interaction between biochar, plants, and AM fungi can contribute to improved plant health and growth.[97] Moreover, owing to its sorption capacity, biochar can effectively regulate interactions among microbes and between microbes and the plant's rhizosphere by disrupting their chemical-based signalling networks. This property of biochar can significantly impact the dynamics of microbial communities in the soil and their interactions with plants, potentially contributing to enhanced plant health.[15]

Biochar increasing soil nutrient availability

The modification of abiotic soil conditions, soil quality, and nutrient availability directly or indirectly affect plant pathogens. Biochar amendment elevates soil pH and increases the concentration of essential soil elements like Mg^{2+}, Ca^{2+}, and K^{+}.[98] The incorporation of biochar and PGPR, A*zotobacter chroococcum* and *Pseudomonas koreensis* in saline–sodic soil significantly improved the soil condition. It improved Mg^{2+}, Ca^{2+}, and K^{+} content and subsequently reduced soil Na^{+} content. Similarly, it also increased soil urease and dehydrogenase making biochar suitable amendment to reduce the ill effect of saline-sodic soil.[99] Consequently, biochar-enriched soil exhibits enhanced nutrient availability, which is utilized by beneficial microorganisms. This, in turn, stimulates the production of growth regulators, including phytohormones and elicitors, ultimately inhibiting pathogen growth and development. This multifaceted impact underscores the significance of biochar in managing plant diseases and promoting overall plant health.[100] Incorporating biochar into the soil increases the carbon-to-nitrogen (C/N) ratio, which, in turn, fosters beneficial microbial activity. This elevated C/N ratio is attributed to the lower nitrogen content in biochar, as much of the nitrogen is removed during the pyrolysis process. The reduced availability of mineral nitrogen hinders the pathogen's saprophytic capabilities and, as a result, impedes the infection process. This phenomenon highlights how biochar contributes to altering soil conditions in a way that promotes plant health and disease resistance.[101]

Biochar positively influences the diversity of the microbial community

Amending the soil with biochar promotes the growth and activities of beneficial microbes. These beneficial microbes, in turn, act as a protective barrier, guarding the plant against attacks from plant pathogens (Table 3). The organic matter within biochar serves as a nutrient source, leading to an increase in microbial biomass, mycorrhizal fungi, and the population of other beneficial bacteria that promote plant growth. The increase and promotion of beneficial microbes can be attributed to both physical as well as nutritional factors and the moisture retention capability of the soil.[102] Numerous empirical pieces of evidence support the efficient utilization of biochar by both beneficial bacteria and mycorrhizal fungi.[103-105] Additionally, the chemical alterations that transpire in biochar during pyrolysis exert negative effects on plant pathogens. Moreover, biochar serves as an organic carbon source that sustains saprophytic growth.[106] Application of wheat biochar favoured soil microorganisms' population and production of soil enzymes such as dehydrogenase (27.5%–70.2%) and polyphenol oxidase (6.6%–69.1%).[107] Post-pyrolysis, biochar transforms into a suitable organic material for promoting sustainable crop performance, albeit with limited microbial sustainability. It has been observed that there is a continuous loss of O-alkyl C and di-O-alkyl C linked to carbohydrates, accompanied by a concurrent increase in aromatic carbons. This shift promotes the saprophytic growth of beneficial microbes and a substantial increase in the yield of onion and rapeseed.[108]

Limitations of biochar application

In the current scenario, much literature has emphasized the usefulness of biochar in sustainable agriculture. However, the negative impact of biochar on soil health should not be ignored. Future research should emphasize limitations that hinder its capacity to address sustainable crop production and climate change. The organic pollutants such as polycyclic aromatic hydrocarbon, furans, and dioxins produced during the pyrolysis of biochar pose potential risks to human health.[109,110] In addition to organic pollutants, they may also contain heavy metals such as Cu, Cd, and Ni. For instance, Copper and Arsenic levels in the soil increase by 30 times upon biochar inoculation which affects soil and plant health.[111,112] Biochar aging due to biotic and abiotic factors leads to its diminishing ability to absorb heavy metals and has an inhibitory effect on soil-inhabiting organisms.[113] In addition, to potential contamination of soil with heavy metals it also led to reduced root biomass in rice and tomato.[114] Many studies have reported increased weed growth upon biochar application. The application of biochar at 15t/ha relatively increased the weed by up to 200% in lentil cultivation.[115] Studies indicate the positive effect of biochar varies from soil to soil, plant species and even plant parts. The application of biochar increased vegetative growth in tomatoes with no influence on fruit yield.[116] Another possible drawback is biochar absorbs nutrients such as N and Fe resulting in nutrient deficiency in plants. Biochar applied to alleviate heavy metal contamination in the lettuce field leads to decreased lettuce growth. This is attributed to the absorption of heavy metal along with available N resulting in N deficiency.[117] Similarly, when biochar and P fertilizer were applied together in saline sodic soil it led to precipitation of P further leading to nutrient deficiency.[118] Lastly, more research and focus is required to understand the limitations of biochar application and ways to mitigate them for sustainable agriculture.

CONCLUSION AND FUTURE PROSPECT

Biochar emerges as a promising tool for enhancing crop yield and safeguarding crops in an eco-friendly and sustainable manner. It offers a cost-effective method that complements environmental conservation. Moreover, biochar contributes to carbon sequestration, increased crop yields, and resilience against various biotic and abiotic stressors. It is produced through pyrolysis, an energy-efficient process. The application of biochar results in alterations in soil physico-chemical properties may not always directly correlate with disease suppression. However, the direct influence on the soil ecosystem provides essential nutrients for microbial growth and plant nourishment. Disease suppression in host plants can also be linked to changes in biochemical properties or physiological responses that activate systemic resistance. Therefore, soil amendment with biochar could play a pivotal role in shaping a sustainable agricultural system for the future.

Nevertheless, future research is imperative to unveil the metabolites involved in the interaction between pathogens and host plants in biochar-applied soil. Further investigations are required to comprehend the disease suppression capabilities and the novel mechanisms at play. The impact of different biochar types on various pathogens remains unexplored, and more research is needed to understand how to enhance beneficial soil microbes without promoting pathogen populations and virulence. A deeper understanding of the chemical and physical characteristics of biochar and their effects on pathogenic microbes, as well as the signaling pathways involved in disease resistance induction, is essential. Most research conducted thus far has been confined to laboratory or greenhouse conditions. Therefore, long-term field studies are necessary to assess the feasibility of biochar against plant diseases. Many farmers and growers remain unaware of the numerous benefits of biochar. Hence, it is crucial to conduct training and workshops to disseminate the promising long-term advantages of biochar in organic agriculture and to establish biochar as a practical approach for controlling plant diseases in the near future.

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The authors declare that there is no conflict of interest.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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The article does not contain any studies on human participants or animals performed by any of the authors.

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