Review Article

Utilizing Biochar for Plant Disease Control: An Organic Strategy

ABSTRACT

Biochar, derived through pyrolysis, presents a promising solution to the challenges faced in sustainable agriculture. This review delves into the diverse advantages of employing biochar to enhance crop yields while promoting environmental responsibility. Its cost-effectiveness and eco-friendly nature not only enrich soil fertility but also contribute to carbon capture, aiding in the fight against climate change. Additionally, while its effectiveness in disease control may vary, biochar shows potential in bolstering crops against environmental pressures. By altering soil characteristics, it encourages the growth of beneficial microbes and improves nutrient availability, ultimately supporting plant vitality. Moreover, integrating biochar into agricultural systems may prompt biochemical and physiological changes that activate plant defences against pathogens. This study thoroughly assesses biochar's impacts on soil health, crop output, and disease prevention, emphasizing its crucial role in advancing sustainable farming practices. Embracing biochar as a strategic resource offers great potential for cultivating resilient and environmentally friendly farming methods, marking a significant step towards sustainable crop diseasemanagement.

Keywords: Biochar, Disease suppression, Soil health, Sustainable agriculture, Crop yield

1. INTRODUCTION

The significant growth in the global population poses significant challenges to both food security and climate change. Projections suggest that the world's population will continue to rise, with estimates ranging from 9.4 to 10.1 billion people by 2050 [1]. With agricultural land becoming increasingly scarce, there is a pressing need for sustainable approaches to address imminent food shortages. The most effective solution is to enhance food productivity within existing constraints [2]. The primary reasons for decreased crop yields can be categorized into two main groups: biotic factors, which include pests, pathogens, and herbivores, and abiotic factors such as salinity, alkalinity, and chilling injuries. Statistics reveal that plant pathogens are responsible for a 26% reduction in yield, with soil-borne pathogens alone contributing to 10-20% of this loss [3, 4]. Traditional agricultural methods rely on agrochemical application, soil disinfection techniques, and the cultivation of resistant crop varieties to manage pests. However, pesticides pose significant environmental risks by harming beneficial soil microbes, polluting aquatic ecosystems, and leading to the accumulation of toxins in the food chain through water and soil pollution [5, 6]. Ongoing efforts advocate for the widespread adoption of long-term sustainable organic farming as a preferable alternative to conventional agricultural practices.

Biochar, as defined by Lehmann et al. [7], is a carbon-rich substance derived from biomass through pyrolysis. Pyrolysis entails the thermal breakdown of organic matter in a high-temperature, oxygen-deprived setting, as elucidated by Lehmann and Joseph [8]. This process occurs within a reactor and leads to the conversion of organic material into diverse solid, liquid, and gaseous by-products. The solid fraction, encompassing fixed carbon and other inorganic components, is recognized as biochar, as outlined by Gheorghe et al. [9] and Yaman [10]. It exhibits potential in effectively combating various disease-causing agents such as fungi, bacteria, nematodes, and insect pests. Beyond its numerous beneficial attributes, biochar also improves soil quality and contributes to carbon storage [11]. Biochar resembles charcoal and is obtained by subjecting plant and animal residues to controlled, low-oxygen conditions via a process termed thermo chemical conversion [12, 13]. Various techniques, including pyrolysis, torrefaction, gasification, flash carbonization, and hydrothermal carbonization, are employed in biochar production. Among these methods, pyrolysis is commonly preferred as the most viable option.

In the Amazon regions, there's a notable presence of black carbon known as Terra Preta, which boasts high levels of carbon, nitrogen, phosphorus, potassium, and magnesium, creating a fertile soil conducive to agricultural productivity [14]. Recent research has highlighted various benefits of biochar use. For example, sugarcane bagasse biochar (SBB) has been utilized to counteract the negative effects of polystyrene micro plastics in rice ecosystems, resulting in reduced methane emissions and improved yield and biomass production [15]. Similarly, SBB has been applied to enhance the growth of corn and rice in soils contaminated with lead and cadmium, leading to increased shoot and root dry weights and demonstrating its effectiveness in remediating polluted soils [16, 17]. The remarkable porosity of biochar creates a favourable environment for microorganisms [14], influencing the structure and function of microbial communities and promoting the use of aromatic carbon sources. Generally, five mechanisms have been proposed to explain biochar's disease-suppressing properties, including enhancing systemic resistance, altering soil physicochemical characteristics, boosting populations of beneficial rhizospheric microorganisms, and releasing fungitoxic and allelopathic compounds, either directly or indirectly. Moreover, both systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways have been observed to contribute to biochar's disease suppression mechanism [18, 19, 20]. The aim of this review is to offer a comprehensive overview of the significance of biochar in promoting sustainable agriculture, particularly focusing on its impact on soil health, disease management, and the mechanisms through which it enhances plant resilience.

2. BIOCHAR IN AGRICULTURE

Biochar plays a pivotal role in agriculture, offering advantageous attributes that positively influence soil health, microbial ecosystems, and plant development. Its porous structure and inherent oxidizing abilities facilitate the generation of beneficial organic compounds, rendering it versatile for applications like water purification, pest management, and fertilizer administration. Moreover, its nutrient richness and retention capabilities make it an effective soil amendment, while its protective mechanisms shield plants from pathogens and aid in environmental rehabilitation. The properties of biochar are intricately linked to the pyrolysis process, which encompasses variables such as heating rate, temperature, duration of exposure, and post-production treatments. Managing these factors allows for tailoring biochar to specific requirements. Various feedstocks and pyrolysis temperatures influence the physical characteristics of biochar; for instance, biochar derived from rice and wheat exhibits higher density compared to that from maize and pearl millet at 400°C. Lower pyrolysis temperatures produce biochar with reduced surface area and ash content, while higher temperatures result in biochar with increased surface area and ash content. Additionally, the chemical composition of biochar is affected by temperature variations. Pyrolysis at lower temperatures (below 400°C) yields biochar with elevated levels of nitrogen, sulfur, potassium, and phosphorus, along with lower carbon content and pH. Conversely, higher temperatures (ranging from 600 to 900°C) generate biochar with decreased nitrogen, sulfur, phosphorus, and potassium content, but with higher carbon content and pH. Furthermore, the choice of raw material also influences the chemical properties of biochar; for instance, biochar derived from rice residue exhibits the highest Cation Exchange Capacity (CEC) [21].

2.1. Enhancing Agriculture through Biochar: A Beneficial Influence

While conventional chemical approaches are commonly utilized for managing plant diseases, they carry notable drawbacks. Pesticide usage results in the accumulation of harmful chemical residues, fosters pesticide resistance in pathogens, and diminishes natural enemies of pests, posing health hazards to farmers and environmental risks such as groundwater pollution [22]. Conversely, biochar offers a sustainable alternative in agriculture. Serving as a soil enhancer, biochar contributes to mitigating climate change by reducing emissions of greenhouse gases and promoting carbon storage owing to its resistance to microbial degradation [23]. Research indicates that the application of biochar, either alone or in combination with fertilizers, enhances crop productivity by approximately 10% [24]. This enhancement arises from various mechanisms: biochar's alkaline properties elevate soil pH, its high capacity for retaining water and nutrients benefits crops, it absorbs and neutralizes harmful substances, and it encourages the proliferation of beneficial microorganisms, all of which support plant well-being [25]. Moreover, biochar contributes to the management of plant diseases by eliciting systemic defense reactions, improving soil characteristics, and maintaining a balanced microbial ecosystem [26].

2.2. Transformative Effects of Biochar on Soil Chemical Properties

Biochar is becoming increasingly popular in agriculture due to its ability to improve essential soil chemical properties such as cation exchange capacity (CEC) and neutralizing soil acidity. This enhancement is attributed to the presence of carboxyl functional groups on the surface of biochar, which contribute to increased alkalinity and CEC. Factors influencing the alkalinity of biochar include the composition of alkaline ash, choice of raw material, and pyrolysis temperature [27, 28]. The main mechanism behind the increase in soil pH buffering capacity is the release of cations resulting from the protonation of carboxyl groups on the surface of biochar and the dissolution of carbonates [29]. Application of biochar improves soil nutrient retention by raising levels of NH_4^+ and Ca^{2+}. Furthermore, it reduces leaching of nitrogen, phosphorus, and potassium, as well as nitrous oxide emissions. It also decreases inorganic nitrogen while increasing organic nitrogen, which stimulates root activity for enhanced nitrogen uptake by plants [30]. The nutrient content of biochar varies depending on the raw material and pyrolysis process, with options such as sludge or manure biochar containing fertilizer elements [31]. Biochar is considered chemically stable, with long-lasting effects due to its dense structure and gradual release of organic carbon as carbon dioxide [32, 33].

2.3. Transformative Effects of Biochar on Soil Physical Properties

Biochar is widely recognized as a potent soil amendment essential for regulating pH levels, improving soil density and thermal properties, stimulating plant growth, enhancing soil structure and fertility, boosting nutrient availability, and augmenting water retention capacity [34]. Its ability to decrease soil density enhances water retention by improving aeration and reducing compaction. Various factors, such as the source material and pyrolysis temperature used in biochar production, as well as the soil type, influence its impact on soil water retention. Notably, while biochar can enhance water retention in sandy and loamy soils, its efficacy may be diminished in clay soils [35]. The influence of biochar on soil physical properties plays a crucial role in shaping microbial communities in the rhizosphere [36, 37].

2.4. Influencing Soil Microbial Communities: The Effect of Biochar

Soil microorganisms play a crucial role in maintaining soil health by facilitating the decomposition of organic matter, cycling nutrients, controlling diseases, and promoting plant growth [38, 39]. While biochar generally resists microbial decomposition, there may be some initial breakdown due to both chemical reactions and microbial activity [40]. The degradation of biochar provides organic nutrients for beneficial microbes such as mycorrhizal fungi and bacteria [41], resulting in an increase in beneficial bacteria and a decrease in harmful fungi [42]. Application of biochar stimulates root growth, fosters microbial growth, and enhances nutrient cycling efficiency [43]. Biochar also influences soil pH, which in turn affects critical microbial populations involved in nutrient cycling and plant disease control, notably increasing the abundance of Actinobacteria and Proteobacteria [44, 45]. The Proteobacteria phylum aids in plant pathogen control by fostering the growth of antagonistic bacteria through nitrogen, carbon, and sulfur cycling [46]. Additionally, it supports the growth of nitrogen-fixing bacteria, thereby increasing biological nitrogen fixation in plants via root nodule formation [47]. The application of biochar enriches the diversity of beneficial microbial communities such as plant growth-promoting rhizobacteria (PGPR), which in turn assists in the cycling of soil organic matter and its availability to plants [48]. Incorporating biochar alters soil microbiota, impacting nitrogen availability by reducing nitrogen mineralization and disrupting the balance between nitrogen oxidizers and reducers [49].

3. BIOCHAR AS A POTENTIAL WEAPON AGAINST PLANT PATHOGENS

In 1847, Allen's report was among the earliest recognitions of biochar's potential in addressing plant diseases such as mildew and rust [50]. Substantial evidence suggests that biochar significantly reduces the occurrence and severity of diseases globally [51]. Biochar provides carbon, supporting the proliferation of lignin-degrading microbes like Dothideomycetes and Actinobacteriales. By promoting the growth of gamma and beta-proteobacteria, it aids in combating fungal pathogens. The application of biochar stimulates the development of beneficial microbes such as *Pseudomonas*, *Serratia*, and *Stenotrophomonas*, which play a crucial role in suppressing fungal pathogens [52].

3.1. Biochar for the Control of Plant Pathogenic Oomycetes

Employing a 5% (vol/vol) concentration of biochar derived from pine plant material initiates the activation of plant defenses, inducing systemic resistance. This effect has been observed in *Quercus rubra*, countering *Phytophthoracinnamomi*, and in *Acer rubrum*, combating *Phytophthoracactorum*. This mechanism helps mitigate disease progression and alleviates physiological stress, as observed by Zwart and Kim [53]. Conversely, the application of softwood biochar resulted in increased root colonization by *Pythiumultimum* in sweet pepper, lettuce, basil, and geranium. Nonetheless, there were no apparent adverse effects on the root system or hindrances in plant growth, as documented by Gravel et al. [54].

3.2. Biochar for the Control of Plant Pathogenic Fungi

The use of hardwood biochar resulted in an increase in the populations of beneficial organisms like arbuscular mycorrhizal fungi (AMFs), as demonstrated by Elmer [55]. Moreover, AMFs have been acknowledged for their role in stimulating systemic resistance, as highlighted in a study by Poveda et al.[56]. These findings strongly suggest that biochar exerts its beneficial effects by altering soil characteristics or nutrient availability and promoting microbial communities in the soil, as discussed in research by Elmer[55] and Elmer and Pignatello[57]. Similar results were observed against pathogens like *F. solani* and *Ilyonectriadestructans* in *Panax ginseng* plants cultivated in soil enriched with rice husk biochar, attributed to changes in the microbial population in the rhizosphere, as demonstrated by Eo et al.[58]. Likewise, incorporating green waste biochar with compost (ranging from 0 to 3% concentration by weight) was found to mitigate *F. oxysporum* f.sp. *lycopersici*-induced wilt in tomatoes, linked to an increase in beneficial microorganisms. These microorganisms could potentially act through direct antagonistic effects or indirectly by inducing systemic resistance in plants, as suggested by Akhter et al.[59]. The positive effect of biochar derived from beech wood chips or garden waste in combating *F. oxysporum* f.sp. *lycopersici* in tomato plants likely arises from its ability to alter substances released by plant roots, which could play a crucial role in plant response to disease pressure, as proposed by Akhter et al.[60]. Additionally, biochar enhances the plant's ability to resist foliar plant pathogenic fungi. The primary mechanism identified for this enhanced resistance involves the systemic activation of defense mechanisms, as observed by Poveda et al.[56].*Botrytis cinerea* is a versatile fungal pathogen responsible for necrotic disease in numerous host plants found across various plant species.

Utilizing biochar derived from various sources, such as holm oak for strawberry fields and eucalyptus wood chips for tomato cultivation, enhances the diversity of bacteria in the rhizosphere. This activation of systemic resistance against pathogens like *B. cinerea* results in a decrease in disease incidence[61]. Additionally, the application of biochar from greenhouse waste in tomato plants triggers early- and late-acting defense responses against *B. cinerea* by stimulating gene expression associated with jasmonic acid and ethylene responses. This process also increases the accumulation of active oxygen species like H_2O_2, which are crucial for resistance[62]. Similarly, the incorporation of citrus wood biochar at varying percentages in tomato and pepper cultivation effectively reduces diseases caused by *B. cinerea* and *Leveillulataurica* (powdery mildew) by inducing systemic resistance[51]. Pepper plant waste biochar also demonstrates effectiveness against fungal pathogens such as *Colletotrichumacutatum* and *Podosphaeraaphanis*[18], which cause anthracnose and powdery mildew in strawberries, respectively[63, 64]. In the *Rosellinianecatrix* - *Perseaamericana*pathosystem, the addition of biochar notably decreases both the severity and occurrence of the disease[65]. There is a strong correlation between biochar and the effectiveness of biocontrol fungus *Trichoderma harzianum* against *Macrophomina phaseolina*[66]. Combining biochar with *Bacillus subtilis* helps mitigate Fusarium wilt in radishes[67]. The potential for disease suppression varies depending on factors such as the diversity of raw materials, production methods, application rates, and soil types[68]. For instance, corn stover biochar effectively manages soybean root rot caused by *Fusariumvirguliforme*, while sawdust and poultry waste biochar significantly reduce maize ear rot caused by *Fusariumverticilloides* [69, 70].

3.3. Biochar for the Control of Plant Pathogenic Bacteria

Recent research has investigated the use of biochar in addressing bacterial plant diseases, particularly focusing on combating bacterial wilt, a significant concern in global vegetable cultivation, attributed to *Ralstonia solanacearum* [71]. The protective effects of biochar result from its capacity to improve soil physical and chemical properties, as well as promote an increased presence of beneficial bacteria and actinomycetes near plant roots. Consequently, this reduces the swarming capability and ability to colonize roots by *R. solanacearum*, as evidenced in studies conducted by Lu et al. [72], and Gu et al. [73].

3.4. Mechanism of plant disease control by application of biochar

Disease management can arise from both direct and indirect factors. The soil environment and the microbiome in the root zone are closely linked, and even small alterations in soil characteristics can affect the makeup of microorganisms surrounding the roots. It's crucial to note that while biochar's direct interactions may have a lesser impact on foliar pathogens, its effects on pathogens inhabiting the soil are typically more significant [74].

3.4.1. Induction of systemic plant defense

When biochar is administered away from the site of infection in foliar diseases, it initiates resistance, indicating systemic activation. This phenomenon may be attributed to chemical triggers, phytotoxic compounds, and the assistance of beneficial microorganisms. Various factors such as volatile compounds, minerals, and free radicals induce resistance in plants. Both systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways contribute to this process by prompting a rapid increase in lipid peroxidation and the production of superoxide. Consequently, free radicals are generated and polyunsaturated fatty acids are altered, ultimately suppressing diseases through systemic resistance [75, 76].

The application of biochar resulted in reduced disease severity in pepper and tomato plants infected with powdery mildew and graymold caused by *L. taurica* and *B. cinerea*, respectively. This decrease was attributed to the activation of induced systemic resistance [51]. Similarly, biochar application lowered the incidence of foliar diseases in strawberries caused by *P. aphanis* and *B. cinerea*, activating systemic resistance against these pathogens [18].

3.4.2. Inhibition of growth and development of pathogens

Biomass pyrolysis involves significant chemical transformations, breaking down O-alkyl carbons associated with carbohydrates while simultaneously producing aliphatic and aromatic carbon compounds [77]. Furthermore, this process can yield organic substances possessing strong antifungal properties. The resultant biochar comprises 29 primary compounds, including fatty acids, dicarboxylic acids, carboxylic acid derivatives, phenolic compounds, and tri-terpene acids. However, it is essential to recognize that the direct toxicity of biochar to pathogens is unlikely the sole reason for disease suppression. Various other mechanisms and factors are likely at play in achieving this outcome [78].

4. LIMITATIONS

Contemporary literature extensively discusses the advantages of integrating biochar into sustainable agriculture. Nonetheless, it's imperative to acknowledge the potential drawbacks of biochar on soil health. Future research endeavors should prioritize identifying limitations that hinder its capacity to promote sustainable crop cultivation and combat climate change. The production of organic pollutants such as polycyclic aromatic hydrocarbons, furans, and dioxins during biochar pyrolysis poses risks to human health [79, 80]. Furthermore, biochar may serve as a reservoir for heavy metals like copper, cadmium, and nickel. For instance, the introduction of biochar could substantially elevate copper and arsenic levels in the soil, adversely affecting both soil quality and plant vitality [81, 82]. Aging biochar, influenced by biological organisms and environmental conditions, diminishes its ability to absorb heavy metals and detrimentally impacts soil-dwelling organisms [83]. Several studies have observed an increase in weed proliferation following the application of biochar, with weed growth rising by as much as 200% in lentil cultivation [84]. Research indicates that the benefits of biochar vary depending on soil composition, plant species, and specific plant components. For example, applying biochar promoted the vegetative growth of tomatoes without affecting fruit yield [85]. Further investigation and attention are warranted to understand the limitations associated with biochar utilization and devise strategies to mitigate them for the advancement of sustainable agricultural practices.

5. CONCLUSION

Biochar emerges as a promising solution for enhancing crop yields and safeguarding crops in a manner that is both environmentally friendly and sustainable. It offers a cost-effective strategy that aligns well with conservation initiatives. Furthermore, biochar contributes to carbon capture, thereby improving crop productivity and resilience to various environmental pressures. Produced via pyrolysis, it represents an energy-efficient process. While the direct relationship between biochar application and disease suppression may vary, it nonetheless supports soil health by promoting microbial growth and supplying essential nutrients to plants. Disease management could also involve biochemical or physiological shifts that activate systemic resistance. Consequently, integrating biochar into soil has the potential to significantly influence the evolution of sustainable agricultural practices.

6. FUTURE PROSPECTS

Future research is crucial to uncover the metabolites involved in the interaction between pathogens and host plants within soil treated with biochar. Further investigations are needed to elucidate the disease-suppressing capabilities and novel mechanisms at play. The impact of different biochar types on diverse pathogens remains unexplored, and additional studies are required to determine methods for promoting beneficial soil microbes without inadvertently increasing pathogen populations and virulence. A deeper comprehension of biochar's chemical and physical properties and their effects on pathogenic microbes, as well as the signalling pathways implicated in inducing disease resistance, is imperative. While most research has been conducted in controlled environments, long-term field studies are essential to assess the practicality of biochar in combating plant diseases. Many farmers lack awareness of the myriad benefits of biochar, underscoring the importance of offering training and workshops to disseminate knowledge about its promising long-term advantages in organic agriculture and establish it as a viable method for disease control in the future.

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