Integrative
Plant Biotechnology
ISSN: 3007-2735 (Online), 3007-2727 (Print)

Review Article

Biochar Application: A Sustainable Approach for Mitigating Biotic and Abiotic Stresses in Plants

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ABSTRACT

Biochar is a carbon-rich material derived from the pyrolysis of biomass has emerged as a sustainable soil amendment for improving plant health and productivity under biotic and abiotic stress conditions. This review examines the multifaceted role of biochar in mitigating plant stresses and emphasizing its potential as a holistic solution for sustainable agriculture. Biochar porous structure and surface chemistry enable enhanced soil properties including improved water retention, nutrient availability and microbial activity which collectively bolster plant resilience to abiotic stresses such as drought, salinity, and heavy metal toxicity. Simultaneously, biochar acts as a biocontrol agent against various plant pathogens and insect pests by altering plant physiological functions (defensive genes), rhizosphere chemistry, promoting beneficial microbial communities and releasing allelopathic chemicals that suppress plant pathogens, insect pests and weeds. Case studies reveal that biochar amendments not only reduce disease severity and pest infestation but also improve crop yield and quality under adverse conditions. Furthermore, biochar role as a carrier for nanoparticles and bio-pesticides presents a novel strategy for integrated pest and disease management. Despite its promising applications, challenges such as variability in biochar properties and their interactions with soil and crop systems require further research. This review consolidates the latest advancements in biochar research highlighting its mechanism of action, applications and limitations while proposing future directions to optimize biochar for stress management. The insights presented aim to support the development of sustainable agricultural practices that enhance food security and environmental resilience.

Keywords: Biochar application, mitigation, abiotic stress, resistance, diseases, insects

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Article History
Received: November 26, 2024
Accepted: December 05, 2024
Published: December 07, 2024

Cite this article
Arshad, U. (2024). Biochar Application: A Sustainable Approach for Mitigating Biotic and Abiotic Stresses in Plants. Integrative Plant Biotechnology, 02, 77-98.

INTRODUCTION

Organic amendments have been embraced as the most effective way of replacing chemicals in organic farming. Several organic approaches have been used in cultivation among which biochar has gained prominence as a resource with several uses. Biochar (BC), the by-product of biomass pyrolysis, is now a mainstay in organic farming though it is used in other principles of sustainable agriculture. Like common charcoal, biochar is produced in a low oxygen atmosphere where carbon is retained for its usefulness in soil improvement (Foong *et al.*, 2020; Ghodake *et al.*, 2021). By sequestering CO_2 in soil, the production of biochar equally greatly helps in climate mitigation in agriculture while enhancing the fertility of soils. The application of biochar is instigated by abundant nutrients in the various Amazonian terra preta soils, with their appreciably high levels of macronutrients (Joseph *et al.*, 2021; Hilbert and Soentgen, 2020). BC is presented as a remedy for various abiotic stresses. BC makes soil permeable while building water retention that protects it during drought (Thao *et al.*, 2024). Salinity is also countered by BC if it is able to deliver nutrients to malnourished soils (Huang *et al.*, 2023). It may adsorb heavy metals like lead and cadmium, producing a reduction in their uptake by plants (Zang *et al.*, 2023).

https://doi.org/10.55627/pbiotech.002.01.0972

Among the different strategies adopted by the plant for better growth and development, enhanced catalase and peroxidase activities protect from harmful levels of reactive oxygen species (ROS) (Haider *et al.*, 2021). Moreover, BC acts as a thermal buffer under extreme conditions, regulating temperature variations for the roots (Xiong *et al.*, 2020). It also modifies the diversity of soil microbial communities in the root zone which enables the plants to better tolerate different stresses through hormone modulation and activating growth-promoting compounds (Ali *et al.*, 2017).

Biochar application is a potent tool for soil enhancement and plant disease management. It can suppress diseases like powdery mildew in tomatoes and strawberries by inducing systemic acquired resistance (SAR), increasing the availability of nutrients, promoting the multiplication and establishment of beneficial microbes, and absorbing toxins and other adverse compounds from the soil (Poveda *et al.*, 2021). Moreover, BC application suppresses soil-borne pathogens such as parasitic nematodes, which enhances plant health across different and mixed farming systems. The composition of BC is dependent on different feedstocks, pyrolysis conditions, and application costs.

For instance, leaf litter from black carbon has a higher amount of carbon concentration compared with leachate or corn stalks agricultural sources (Brewer *et al.*, 2011). Such modifications may influence the competency of BC in combating some of the issues, which include disease management and stress alleviation. Capabilities This review synthesizes more than 100 studies and demonstrates the significance of BC towards the achievement of sustainable agriculture practices. BC provides a way to improve plant health and improve environmental management by reducing biological disease and stress.

IMPACT OF BIOCHAR APPLICATION

Biochar positively affects plant performance, including biotic and abiotic stress conditions. The benefits of biochar are relevant and far more diverse than mere benefits in respect of promoting plant health, offering environmental benefits that bear on soil quality and global ecological balance. Biochar has been proven to enhance the fertility of the soil, and therefore it plays an important role in curbing global warming. Key characteristics of biochar include carbon sequestration, which enhances photosynthetic efficiency but slows down the rate of degradation of photosynthetic products and thus decreases carbon dioxide in the atmosphere (Woolf *et al.*, 2010).

Biochar production impacts the carbon cycle and thus significantly decreases atmospheric greenhouse gas concentration. The application of biochar (BC) also improves the soil structure exactly the way fertile terra preta soils enhance their capacity to stimulate crop growth and adsorb pollutants in specific locations (Paterson and Lima, 2018). Besides that, BC is given two major roles: soil adaptation and prevention of contamination. It has been proved that BC has a great ability to adsorb a wide variety of dangerous substances, including heavy metals lead, and organic pollutants. Those chemicals are toxic and will degrade the soil and human, animal, and plant health. Thus, regarding the economic benefits and environmental advantages, BC is assumed to be an excellent option for environmental contaminant control. BC loaded with activated carbon has proven to be a material of an equivalent capacity to adsorb and possibly remove toxic pollutants such as herbicides like atrazine (Jeirani *et al.*, 2017).

Although no standard application rate of BC exists, field trials have assessed a remarkably wide range of application rates from 1 to 200 t ha^{-1} by Kammann *et al.*, 2011; Peake *et al.*, 2014. The scope for bespoke applications further helps to accommodate the disparate requirements of soil and environment, bringing out the versatility and practicality of BC in sustainable agriculture and environmental management.

BIOCHAR APPLICATION TO MANAGE PLANTS UNDER ABIOTIC STRESSES

Biochar is provided as a transformative amendment to soils for the enhancement of tolerance to abiotic stress in agricultural systems with characteristic properties such as porosity, cation exchange capacity, and alkaline pH for a potential amelioration of retention of water and availability of nutrients and pH-buffering which are important for plant resilience under stress conditions that can be exerted by drought, salinity, or heavy metal contamination. Biochar acts as an inert habitat for favorable microbes; therefore, it modifies nutrient cycling and activates the enzymes that decrease oxidative stress in plants.

Furthermore, biochar's immobilizing capacity for toxic elements such as cadmium and lead reduce their availability to plants, thereby reducing metal-induced stress in plants and providing safer agricultural practices (Lehmann and Joseph, 2015; Fareed *et al.*, 2024) (Figure 1). All these functions together to enhance soil health and agricultural productivity, and are linked with increasing environmental problems to the benefit of sustainable agriculture.

Improved Soil Physical Properties

Environmental stresses like drought, salinity, cold, and heat significantly affect soil physical properties that generally compromise agricultural productivity. Besides these factors, these stresses often have adverse effects on the structure, specifically the water retention capacity and porosity that are essential for the proper growth of plants. BC improves the attributes of soils due to its porous structure and large surface area, reducing abiotic stresses' impacts (Chi *et al.*, 2024). Biochar improves the stability of soil aggregation and decreases in bulk density, which results in greater soil water infiltration and holding capacity. This is very helpful in drought periods as soils amended with biochar often possess greater moisture availability that supports plant resilience. Additionally, the high porosity of biochar has improved soil aeration, which increases root respiration and microbial activity, which are very important aspects of nutrient cycling and soil health in general (Singh *et al.*, 2022).

These properties enhance permeability in saline soils through biochar application alongside leaching out excess salts corresponding to reducing salinity stress. Alkalinity buffers soil pH levels to a more favorable point for plant growth. Its thermal properties also moderate the fluctuations of soil temperature and buffer thermal extremes around the roots and organisms in the soil. All these have made biochar a promising amendment for improving soil physical properties and mitigating the negative effects of various abiotic stresses (Wu *et al.*, 2023) (Figure 1). Table 1 shows the effect of biochar application in different crop plants under abiotic stresses.

Nutrient Management

Biochar, however, having been highly in carbon with the pyrolysis of organic biomass, has also been significantly kept under consideration to mitigate these negative consequences. High porosity and CEC facilitate it to hold a greater reserve of nutrients and help to let them out into stressed soils (Upadhyay *et al.*, 2024). Biochar application retains the nutrient because it assimilates nutrients with ionic fractions, for example, nitrogen (N), phosphorus (P), and potassium (K), thus minimizing the loss through these essential nutrients. This is very crucial in sandy soils and under drought stress conditions, where water and nutrient losses are highly yielded. For instance, it has been demonstrated that the application of biochar decreased nitrate leaching by 30% while enhancing the nitrogen-use efficiency of maize crops (Wu *et al.*, 2023).

Biochar application reduces salinity stress in saline soils, primarily through the adsorption of excess sodium ions and enhancing nutrient availability to the plants. It is also alkaline in nature, which modifies the pH of the soil, hence allowing better nutrient uptake. Biochar application in saline paddy fields has recently been reported to reduce ion toxicity by as much as 18% and increase rice yield. (Wani *et al.*, 2022). This further encourages the soil microbial communities as well, which significantly play an essential role in nutrient cycling. Its porous nature supports microbes, thus speeding processes that include nitrogen fixation and phosphorus solubilization. Results of several studies reported a 25–40% increase in microbial biomass within soils amended with biochar, thus increasing mineralization of organic nutrients, and improving the fertility of the soil (Shahin *et al.*, 2022).

Heavy Metal Immobilization

Biochar applications generally immobilize heavy metals in contaminated soils because it had structural and chemical properties (Ren *et al.*, 2024). The surface area mainly consists of pores that were filled by several adsorption sites, and toxic metals attached to the surface can form strong, stable bonds between functional groups and the toxic metals (Zhang *et al.*, 2013). These bonds thereby reduce the bioavailability and mobility of the metals (Guo *et al.*, 2020). More importantly, its high pH level considerably neutralizes the acidic soils and could possibly cause the heavy metals to precipitate as hydroxides, and its CEC enhances the retention of positively charged ions like Cd, Pb, and Zn (Zhang *et al.*, 2023). All these properties make biochar one of the most efficient mediums used in order to remediate contaminated soils. Among the many mechanisms by which biochar immobilizes heavy metals, some are adsorption, ion exchange, complexation, and precipitation (Figure 1) (Table 1).

Biochar uses different mechanisms for this purpose Adsorption: heavy metals tightly bound through both physical and chemical bonds on the surface of biochar and Ion exchange: poisonous metal ions can be substituted by non-toxic ions for instance, calcium or magnesium. Complexation is when functional groups of biochar combine with metals to produce stable compounds and Precipitation brings metals into insoluble forms and hence non-mobile (Ambaye *et al.*, 2021). Recent research indicates that the incorporation of biochar into Cd-contaminated soils decreased Cd bioavailability by 50% and it restrained uptake to crops like rice; however, in Pb-contaminated soils, biochar minimized the movement of Pb by up to 60% considerably improved soil quality (Kim *et al.*, 2015) (Figure 1) (Table 1). Biochar is the most potent technology in governing heavy metal pollution with abiotic stress conditions of salinity, drought, and extreme temperatures. Biochar reduces the availability of toxic metals to the soil in saline soils characterized by enhanced solubility of metals through adsorption and pH buffering of the soil. For instance, following application, in saline Cd-contaminated soils, biochar reduced the metal's availability by 40%, which meant favorable conditions for salt-tolerant crops (Huang *et al.*, 2023).

Table 1. Effect of biochar application in different crop plants under abiotic stresses.

Stress	Plant	Biochar Concentration Applied	Observation	References
Salinity	*Triticum aestivum* (Wheat)	0%, 15%, 30%, 45% (w/w)	No germination without biochar; germination increased to 48.9% at 45% biochar concentration	(Wang *et al.*, 2013)
Drought	*Glycine max* (Soybean)	10 t/ha, 20 t/ha	Significant reduction in proline content under stress conditions	(Hafeez *et al.*, 2017)
Drought	*Solanum lycopersicum* (Tomato)	0, 25, 50 t/ha	Enhanced yield, physiology, and growth under deficit irrigation	(Agbna *et al.*, 2017)
Drought	*Triticum aestivum* (Wheat)	28 g/kg, 38 g/kg (w/w)	Improved nitrogen mineralization, soil respiration, organic matter, and plant growth	(Zaheer *et al.*, 2021)
Drought	*Capsicum annuum* (Chickpea)	3% (w/w)	Improved root and shoot weights, relative water content (RWC), chlorophyll, and antioxidant activity	(Hashem *et al.*, 2019)
Drought	*Solanum melongena* (Eggplant)	500 g/m²	Improved yield attributes, chlorophyll content, and antioxidant activity	(Ebrahimi *et al.*, 2021)
Drought	*Ehritia asperula*	15 t/ha	Increased biomass and physiological parameters	(Hoang *et al.*, 2021)
Drought	*Brassica oleracea* (Cabbage)	10% (w/w)	Enhanced photosynthesis, nutrient uptake, RWC, proline, and sucrose contents	(Yildrim *et al.*, 2021)
Drought	*Phragmites karka*	0.75%, 2.5% (w/w)	Increased chlorophyll, photosynthesis rate, water use efficiency (WUE), soil water-holding capacity (WHC), and water retention	(Abideen *et al.*, 2020)
Drought	*Triticum aestivum* (Wheat)	37.18 g/kg	Significantly improved tillering, grain yield, and physiological parameters	(Haider *et al.*, 2020)
Drought and Salinity	*Solanum lycopersicum* (Tomato)	0%, 1% (w/w)	Slight increase in total soluble solids (TSS) and vitamin C (VC) under varying irrigation levels	(Wu *et al.*, 2022)
Drought and Salinity	*Chenopodium quinoa* (Quinoa)	5% (w/w)	Enhanced plant height, shoot biomass, grain yield, and WUE; absorbed excess Na+	(Yang *et al.*, 2020)
Salinity	*Solanum tuberosum* (Potato)	5% (w/w)	Alleviated salinity stress by improving Na+ absorption, increasing shoot biomass, root length, leaf water potential, and stomatal conductance	(Akhtar *et al.*, 2015)
Salinity	*Glycine max* cv. M7 (Soybean)	50 and 100 g/kg soil (w/w)	Improved growth, leaf area, shoot/root weight, chlorophyll content, nitrogen metabolism, and RuBisCO activity	(Farhangi-Abriz and Torabian, 2018)
Salinity	*Oryza sativa* (Rice), (*Jinyuan* 85, *Nipponbare*)	0.3% (w/w)	Reduced salt stress, improved soil properties, decreased Na and Cl ions, enhanced root growth and nutrient transport	(Zhang *et al.*, 2019)
Salinity	*Triticum aestivum* (Wheat, HD 2976)	2.5%, 5% (w/w)	Enhanced micronutrient levels, cation exchange capacity (CEC), water-holding capacity (WHC), soil pH, and antioxidative repair system; optimal at 5%	(Ghosh *et al.*, 2021)
Cd Toxicity	*Spinacia oleracea* (Spinach)	3%, 5% (w/w)	Mitigated Cd toxicity, increased growth, protein content, photosynthesis, and decreased Cd and malondialdehyde content	(Younis *et al.*, 2016)
Cd and Drought	*Oryza sativa* (Rice)	3.0%, 5.0% (w/w)	Increased plant height, biomass, photosynthesis; reduced oxidative stress and	(Rizwan *et al.*, 2018)

			bioavailable Cd; increased soil EC and pH	
Cd and Drought	*Triticum aestivum* (Wheat)	3.0%, 5.0% (w/w)	Enhanced physiological, morphological, and antioxidant enzyme characteristics; reduced oxidative stress and Cd content	(Abbas *et al.*, 2018)
Heavy Metal Toxicity (Pb and Zn)	*Zea mays* (Maize)	1%, 2%, 5% (w/w)	Improved growth, reduced heavy metal uptake, increased biomass (41%) and grain yield (50%)	(Xu *et al.*, 2016)
Cd Contamination and Drought	*Triticum aestivum* (Wheat)	3%, 5% (w/w)	Enhanced physiological, morphological, and antioxidant enzyme characteristics; reduced oxidative stress and Cd content	(Abbas *et al.*, 2018)
Heavy metal	*Brassica chinensis* L.	2%	enhanced urease, sucrase, and catalase activities in addition to increase biomass of the plants	(Chen *et al.*, 2020a)
Simulated Nitrogen Deposition	*Torreya grandis*	0, 20 t/ha	Increased nut and kernel weight, size, and nutritional components; decreased soil pH and fertility; biochar improved nut quality and soil fertility	(Zhang *et al.*, 2017)
Reduced Nitrogen Application	*Solanum lycopersicum* (Tomato)	30, 50, 70 t/ha	Improved growth and soil microenvironment with reduced nitrogen fertilizer application	(Guo *et al.*, 2021)
Salinity	*Triticum aestivum* (Wheat, Yannong-19)	0%, 5%, 10%, 15% (w/w)	Germination increased to 48.9% at 45% biochar concentration; no germination without biochar	(Wang *et al.*, 2013)

Biochar enhances the retention of soil moisture in drought-prone regions and hence allows for easier diffusion of heavy metal concentrations in soil besides reducing their uptake by plants. Biochar stabilizes heavy metals due to transformation into insoluble forms under warm conditions, preventing the degradation of soil organic matter (Wei *et al.*, 2023).

Reduction of Oxidative Stress

Due to overproduction of ROS, plants developing abiotic stresses such as drought, salinity, and heavy metal contamination suffer from oxidative stress leading to various damage in cellular functions and crop yield (Figure 1). The application of biochar is considered one of the essential promising strategies that reduce oxidative stress in plants under such stressed conditions. Many studies were conducted recently proving that biochar enhances the characteristics of the soil, which in turn enhances the health and resistance of plants against oxidative damage (Upadhyay *et al.*, 2024). Some of the major ways by which biochar can lead to the alleviation of oxidative stress include improving nutrient availability and water retention in the soil. Biochar alters the physical structure of soil and increases cation exchange capacity, thus enhancing nutrient uptake efficiently as well as making water available for plants. The improved nutrient and water status favors the efficient continuation of physiological processes in plants during stress conditions hence minimizing the generation of ROS Wani *et al.*, 2022).

Besides these, biochar has been shown to play a role in the modulation of antioxidant enzymes of plants. For instance, it has been indicated that an experiment on pea *Pisum sativum* growing under saline conditions, when treated with biochar, observed the high activities of superoxide dismutase SOD and catalase CAT, which are important scavengers of ROS. This way, enzymatic induction eventually leads to the reduction of oxidative damage and promotes growth along with stress tolerance (Fareed *et al.*, 2024). Further, biochar immobilizes heavy metals in contaminated soils would also decrease oxidative stress in plants. Biochar reduces the bioavailability of heavy metals through adsorption hence limiting their uptake into the plants and subsequent generation of ROS. The reduction in oxidative stress leads to healthier and more productive plants in polluted environments (Shahin *et al.*, 2022).

Thermal Stress Mitigation

High soil temperatures have been known to negatively influence growth parameters through interference with physiological processes and generally low crop yield (Rehman *et al.*, 2009) (Figure 1). Applying biochar has been recognized as a method to alleviate thermal stress in plants (Zeeshan *et al.*, 2023). Recent research indicates that incorporating biochar into soil enhances its physio-chemical properties, such as increasing organic matter content and bulk density, which collectively improve plant resilience to heat stress (Zeeshan *et al.*, 2023).

The effectiveness of biochar in reducing combustion heat depends on the pyrolysis temperature. Biochar produced at higher temperatures shows potential for carbon sequestration that can be regulated and stabilized, while biochar produced at lower temperatures significantly benefits soil fertility and nutrient availability. These properties underscore the importance of biochar in mitigating soil and environmental conditions (Tomczyk *et al.*, 2020). Using biochar in agricultural soils also enhances soil quality and supports sustainable waste management practices (Kracmarova-Farren *et al.*, 2024). For instance, biochars derived from wood residues and bones, when applied to various soil types, positively impact the microbial community, thereby improving soil health. Additionally, biochar can boost plant stress resistance by creating better soil conditions for growth (Kracmarova-Farren *et al.*, 2024) (Figure 1).

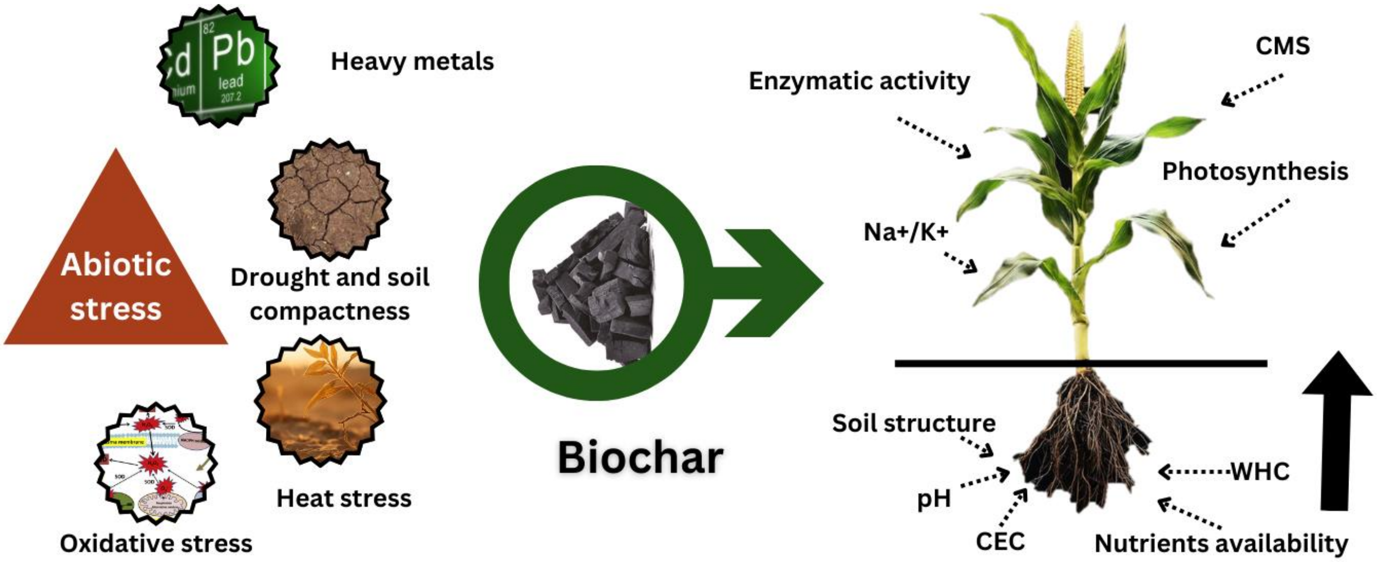

Figure 1. Effects of biochar application on plant resilience to Heavy metals, drought and soil compactness, heat stress, and oxidative stress.

Microbial Interactions

The application of biochar has been demonstrated to enhance the activity of microbes in the soil. This is attributed to the high metabolic rate of microorganisms and the augmentation of beneficial ones. This enhanced microbial metabolism represents a vital force for increasing soil fertility and tolerance to various abiotic stresses (Gorovtsov *et al.*, 2020; Wang *et al.*, 2024). The incorporation of BC has been observed to disrupt the composition and intensity of soil microbial populations, while simultaneously enhancing microbial biomass and diversity. The amendment of soils with BC has been demonstrated to be positively correlated with improved nutrient availability and soil degradation, which are crucial for the sustainability of soil health (Saifullah *et al.*, 2018). Furthermore, it has been demonstrated that BC significantly reduces the uptake of heavy metals by plants in polluted soils, thereby mitigating the toxic effects of metals on microorganisms and maintaining microbial population balance (Yang *et al.*, 2023; Ouyang *et al.*, 2023). In the context of environmental stresses, such as salinity and drought, the positive impacts of BC on soil microbial communities are evident. BC addition increases soil moisture content and provides essential nutrients, thereby enhancing plant performance and resilience to stress (Zhang *et al.*, 2020). Furthermore, the capacity of biochar to maintain soil pH can additionally improve the quality of the microhabitat, thereby enabling microbes to facilitate plant growth promotion under conditions of severe stress (Upadhyay *et al.*, 2024; Wu *et al.*, 2023).

Furthermore, the application of biochar has been linked to an enhanced capacity for nutrient retention, as it possesses the ability to adsorb essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), which would otherwise be lost through leaching. This aspect is particularly significant when biochar is utilized in sandy soils, specifically during drought conditions. For instance, research has demonstrated that the application of biochar has the potential to reduce nitrate leachability by 30% which means a better use of nitrogen in maize farming (Wu *et al.*, 2023; Hossain *et al.*, 2020). Through its cation-exchange capabilities, which aid in the adsorption of excess sodium ions and improve the availability of crucial nutrients to plants, biochar can reduce salinity stress. By further lowering the pH of the soil, it improves the conditions for nutrient absorption. The study's conclusions showed that adding biochar to rice cultivated in saline paddy fields reduced ion toxicity and increased yield by 18% (Wani *et al.*, 2022; Huang *et al.*, 2022).

BIOCHAR APPLICATION FOR DISEASE RESISTANCE IN PLANTS

The roots of the concept of using BC for disease resistance are in studies carried out over a century ago, which showed that certain soil pathogens cause damping-off disease in pine nurseries and that adding charcoal to the nursery potting mix can stop it (Retan, 1915) (Figure 2). BC's antifungal qualities are widely known. It has been demonstrated that BC shields plants from a variety of diseases, such as viruses, fungi, bacteria, and even nematodes (Iacomino *et al.*, 2022). BC has been shown to improve anticipatory defense responses in plants due to its advantageous qualities. Namely, this pertains to the so-called systemic SAR where such pathogenesis-related (PR) proteins are activated by a burst of salicylic acid.

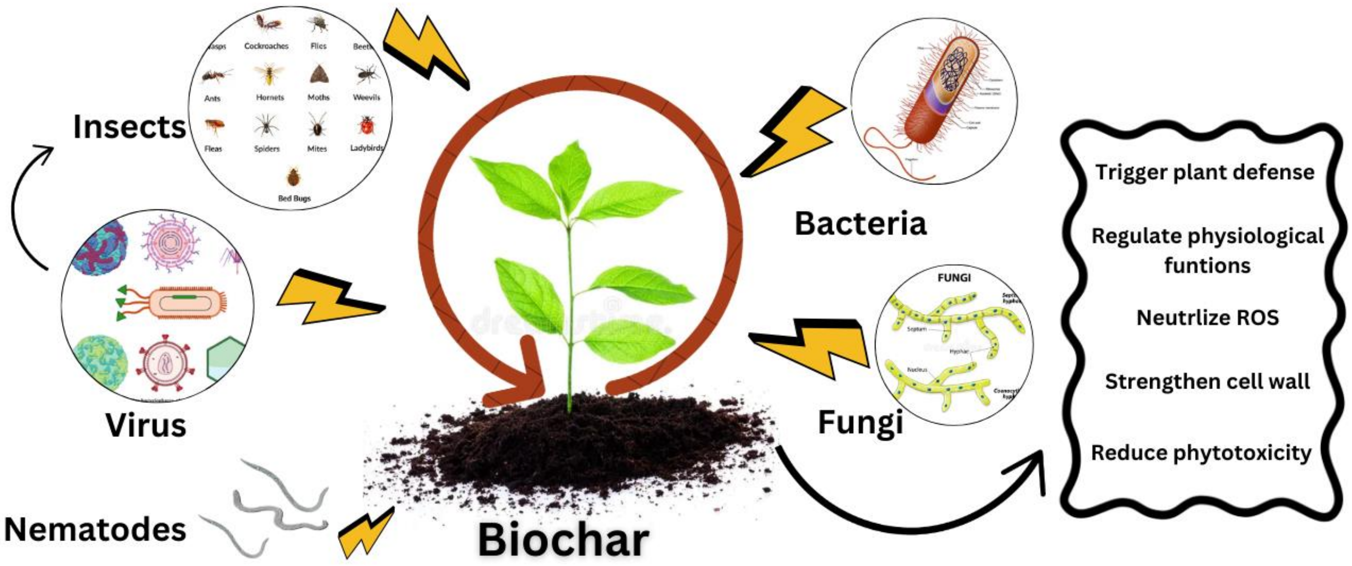

Figure 2. Effects of biochar application to plant fortification against Fungi, Bacteria, Insects, Viruses and Nematodes and enhance plant immunity by triggering plant defense mechanism.

Such responses can also be caused by host plant response to chemical or biological elicitors (Vallad and Goodman, 2004) (Figure 2). Two main mechanisms can be identified: Two major forms of induced resistance to pathogens by plants are SAR and ISR. Salicylic acid-mediated SAR usually involves then expression of PR proteins and is usually associated with an enhanced hypersensitive response towards pathogens. Instead, ISR is the result of colonization with beneficial plant-associated bacteria such as plant growth-promoting rhizobacteria (PGPR) fungi (PGPF) and is mediated through different signaling pathways (Van der Ent *et al.*, 2009).

Studies presented by Elad *et al.*, (2010), Vaccari *et al.*, (2011), and Zwart and Kim (2012) indicate that biochar, which has its origins in many raw material sources, increases plant health and disease resistance while enhancing plant growth and yield. Some of the most important functions of biochar (BC) include the sorption of various toxic compounds, such as water-soluble cell wall-degrading enzymes like cellulase and pectin lyases produced by pathogens of a soil nature. These so-called cell wall degrading enzymes (CWDE), together with other mycotoxins secreted by fungi, contribute to the survival as well as the majority of pathogens needed for digestion and infection. Biochar (BC) plants could also protect plants against pathogen attacks by sorbing and sequestering these toxic substances in soils (Lammirato *et al.*, 2011). Thus, biochar is considered an excellent tool for modern sustainable agriculture, promoting the activation of plant defenses along with the neutralization of hazardous compounds (Figure 2).

Resistance against fungal diseases

Biochar has been reported to beneficially influence microbial communities in Eo *et al.*, (2018) who demonstrated the suppressive action of rice husk biochar in the treatment of fungal pathogens like *Ilyonectria destructans* and *Fusarium solani* in *Panax ginseng* plants. The application of 3% wood waste biochar to potting soil reduced infections by *Fusarium oxysporum* and *Alternaria solani* in tomatoes, which was linked to increased beneficial microorganisms that may act directly against the fungi or elicit SAR in plants (Akhtar *et al.*, 2016).

For example, at the stem base, stem base, biochar of 1-3% green waste was taken as an inducing agent for the sustained resistance of tomato plants to crown rot disease caused by *Fusarium oxysporum* f.sp. *radices lycopersici* (Jaiswal *et al.*, 2020). Further studies have demonstrated the ability of soil incorporation of charcoal in suppressing

https://doi.org/10.55627/pbiotech.002.01.0972

the growth of Fusarium, and other fungi (Silva *et al.*, 2020). Likewise, biochar diversifies the microbial communities present in the soil.

Table 2. Effects of BC applications on fungal plant pathogens.

Pathogen	Host	Biochar Source	Application Rate	Mechanism	References
Botrytis cinerea	*Fragaria* × *ananassa* (Strawberries)	Holm oak	1-3%	Boosted the population of beneficial bacteria in the rhizosphere	(De Tender *et al.* 2016)
Rhizoctonia solani	*Cucumis sativus* (Cucumber) & *Phaseolus vulgaris* (Beans)	Eucalyptus biochar	1% (w/w)	Reduced fungal infection in the soil	(Jaiswal *et al.* 2018)
Botrytis cineria	*Solanum lycopersicum* (Tomato)	Eucalyptus wood chip	1% (w/w)	Increased microbial diversity in the rhizosphere and enhanced plant resistance	(Kolton *et al.* 2017)
Ilyonectria destructans	*Panax ginseng* (Ginseng)	Rice husk	5.2 Mg ha–1	Reduced soil-borne fungal activity by promoting beneficial microorganisms	(Eo *et al.* 2018)
Leveillula taurica	*Capsicum annuum* (Sweet pepper)	Organic biochar	na	Improved soil organic matter and conductivity, enhancing soil health	(Kumar *et al.* 2018)
Fusarium oxysporum f. sp. radicis lycopersici	*Solanum lycopersicum* (Tomato)	Greenhouse waste	1-3% (w/w)	Decreased disease occurrence in plants	(Jaiswal *et al.* 2020)
Fusarium oxysporum	*Stellaria media* (False starwort)	Hull	3%	Reduced disease incidence by improving soil health	(Wu *et al.* 2020)
Fusarium verticillioides	*Zea mays* (Maize)	Poultry waste & sawdust	1-3% (w/w)	Helped reduce overall disease attack in plants	(Akanmu *et al.* 2020)
Fusarium oxysporum and Alternaria solani	*Solanum lycopersicum* (Tomato)	Wood waste	3% (w/w)	Induced systemic resistance in plants through biochar application	(Rasool *et al.* 2021)
Verticillium dahliae	*Solanum melongena* (Eggplant)	Rice husk	10 t/ha	Enhanced beneficial soil microorganisms and reduced disease severity	(Ogundeji *et al.* 2021)
Fusarium oxysporum f. sp. lactucae and Rhizoctonia solani	*Lactuca sativa* (Lettuce) & *Solanum lycopersicum* (Tomato)	na	na	Improved soil health and reduced root pathogen activity	(Bonanomi *et al.* 2022)

Aeo *et al.*, (2018) reported that rice husk biochar effectively reduces the growth of fungal pathogens *Ilyonectria destructans* and *Fusarium solani* in ginseng. When applied in tomato, 1% eucalyptus biochar increases the microbial diversity and resistance grey mold disease caused *Botrytis cinerea* (Kolton *et al.*, 2017). Combined application of poultry litter and sawdust biochar in the proportions of 1–3% efficiently controls *Fusarium verticillioides*, the causative agent for corn ear rot (Akanmu *et al.*, 2020).

The present literature review connects BC as one of the useful approaches to manage soil-borne necrotrophic fungi and crop diseases caused by fungal pathogens. Jaiswal *et al.*, (2018) reported that 1% eucalyptus leaves BC and found that it reduced cucumber and legume diseases which were caused by *Rhizoctonia solani*. De Tender *et al.*, (2016) demonstrated that holm oak BC (1–3%) could suppress *Botrytis cinerea* in strawberries and be utilized to reduce disease transmission, and enhance beneficial root-zone microbes. Organic biochar reduces powdery mildew

(*Leveillula taurica*) in bell pepper, most probably by improving the availability of soil resources and plant biomass (Kumar *et al.*, 2018).

Organic amendments increase the efficiency of biochar. For example, biochar integrated with organic treatments lowers *Fusarium oxysporum* in lettuce and *Rhizoctonia solani* in tomatoes, and therefore it improves soil health (Bonanomi *et al.*, 2022). A new strategy of 3% bark extract from medicinal plants, such as *Lamiastrum galeobdolon*, blended with biochar substantially lowered *Fusarium* wilt and enhanced soil health (Wu *et al.*, 2020). Additionally, field trials show rice biochar (10 t/ha) mitigates Verticillium wilt in eggplants by promoting rhizosphere microbiomes, aiding plant growth and disease suppression (Ogundeji *et al.*, 2021). Table 2 summarizes the impact of BC applications on fungal pathogens in various crop plants.

Resistance against bacterial diseases

Biochar also enhances resistance to bacterial diseases, such as *Ralstonia solanacearum*, the chief bacterial pathogen causing wilt in vegetables. Peanut biochar (2%) and rice husk biochar (3%) significantly decrease tomato diseases (Lu *et al.*, 2016; Gu *et al.*, 2017). Wheat straw biochar further decreases tomato wilt (Tian *et al.*, 2021). Biochar from peanut shells and rice husks increases the number of beneficial bacteria while decreasing the number of pathogens (Wong *et al.*, 2019). Applying rice husk biochar at 45 t/ha in tobacco also lowered wilt incidence through increased beneficial bacteria counts and reduced denitrifier populations (Figure 2). Table 3 summarizes the impact of BC application on bacterial pathogens in various crop plants.

Table 3. Effects of BC applications on fungal plant pathogens.

Pathogen	Host	Biochar Source	Application Rate	Mechanism	References
Ralstonia solanacearum	*Solanum lycopersicum* (Tomato)	Peanut shell	2% (w/w)	Suppressed disease incidence	(Lu *et al.*, 2016)
Ralstonia solanacearum	*Solanum lycopersicum* (Tomato)	Rice husk	3% (w/w)	Suppressed disease incidence	(Gu *et al.*, 2017)
Kosakonia sacchari	na	Peanut shell & Rice husk	5-10%	Improved soil bacterial community	(Wong *et al.*, 2019)
Agrobacterium tumefaciens	na	na	na	na	(Bonanomi *et al.*, 2018)
Streptomyces scabies	na	na	na	na	(El-Hafez *et al.*, 2021)
Ralstonia solanacearum	*Solanum lycopersicum* (Tomato)	Wheat straw	na	Controlled bacterial wilt disease	(Tian *et al.*, 2021)
Ralstonia solanacearum	*Nicotiana tabacum* (Tobacco)	Rice hull	45 t/ha	Enhanced beneficial bacterial population and reduced disease	(Chen *et al.*, 2020b)

Resistance against nematode diseases

Plant parasitic nematodes are devastating pathogens of crops and ornamental plants (Din *et al.*, 2017). The literature demonstrates that biochar application has been very effective on soil nematode populations and has led to considerable nematode reduction (Arshad *et al.*, 2021). Root-knot nematodes (RKNs) and cyst nematodes (CNs) have been challenged with the biochar application in different crop plants. Van Nguyen *et al.*, (2022) reported that a high rate of application (10 Mg/ha) of rice husk BC on soybean fields managed by green manures led to a reductive infection by the soybean cyst nematode (SCN). In another study, Cao *et al.*, (2018) used plant waste-based biochar at a rate of 8 t/ha in cucumber fields and reported an improvement in the physiochemical properties of the soil with decreased RKNs populations (*Meloidogyne* spp.). It was demonstrated that applications of holm oak wood-based biochar (1.2%) in potting media activated resistance in rice against the rice root-knot nematode *M. graminicola* that is mediated by induction of ethylene and jasmonic acid defense pathways (Huang *et al.*, 2015).

Recently, Arshad *et al.* (2020) used rice husk and wheat straw BC at concentrations of 3–5% in the potting medium which significantly reduced the number of *M. incognita* juveniles invading root systems. They further reported that this reduction in nematode population was achieved by activation of defense pathways followed by BC application.

Another indirect method of promoting plant growth is to enhance soil silica content through the addition of BC developed from rice husk. This is because silica, which is abundant in rice plants (up to 10% in dry form), leads to enhanced systemic resistance and ultimately increased biomass against nematodes (Neogi *et al.*, 2022). The application of burned wood BC (4%) has been demonstrated to effectively suppress *Pratylenchus coffeae*, a migratory endoparasite, and root-destructive lesion nematodes in bananas (Rahayu and Sari, 2017; Muthusamy *et al.*, 2019). The induction of systemic resistance has also been demonstrated to be an effective method for reducing the infection of *Pratylenchus penetrans* in carrots when 5% (v/v) coniferous wood and spelt husk BC are applied (George *et al.*, 2016). The direct toxicity of BC against plant-parasitic nematodes (PPNs) and the impact of BC on soil pH remain inconclusive. However, another study found that a combination of coconut shell BC with 1,3-dichloropropene and chloropicrin (40 t/ha) reduced various PPN species (*Pratylenchus*, *Meloidogyne*, *Tylenchorhynchus*, *Tylenchidae*, and *Trichodorus*) while mitigating pollutant emissions (Gao *et al.*, 2018). The combination of neem wood BC (1.2%) and vermicompost was observed to reduce *Meloidogyne graminicola* populations and normalize root infection (Mondal *et al.*, 2021). Moreover, an aqueous solution of grape wine BC prepared at 350°C, was found to be an effective control measure for *Meloidogyne incognita* in tomato plants. This was attributed to the release of macro- and micronutrients that enhanced the activity of beneficial soil microbes (Martínez-Gómez *et al.*, 2023). Table 4 summarizes the impact of BC application on plant parasitic nematodes in various crop plants.

Table 4. Effects of BC applications on plant parasitic nematodes.

Pathogen	Host	Biochar Source	Application Rate	Mechanism	References
Meloidogyne graminicola	Oryza sativa (Rice)	Neem wood	1.2% (w/w)	Reduced nematode population and normalized infection	(Mondal *et al.*, 2021)
Meloidogyne graminicola	Oryza sativa (Rice)	Holm oak wood	1.2% (w/w)	Triggered various defense pathways in the plant	(Huang *et al.*, 2015)
Meloidogyne incognita	Solanum lycopersicum (Tomato)	Grape wine	na	Release of macro- and micronutrients that enhanced the activity of beneficial soil microbes	(Martínez-Gómez *et al.*, 2023)
Meloidogyne incognita	Solanum lycopersicum (Tomato)	Rice husk and Wheat straw	3-5% (w/w)	Reduced nematode infection and inhibited invasion	(Arshad *et al.*, 2020)
Pratylenchus coffeae	Musa spp. (Banana)	Wood	4% (w/w)	Overall reduction in nematode infection	(Rahayu and Sari, 2017)
Pratylenchus penetrans	Daucus carota (Carrot)	Coniferous wood and Spelt husks	5% (v/v)	Altered soil pH and induced resistance	(George *et al.*, 2016)
Pratylenchus, Meloidogyne, Tylenchorhynchus, Tylenchidae,	Commercial orchards	Coconut shell	40 t/ha	Prevented toxic fumigant emission and reduced nematode population	(Gao *et al.*, 2018)

Resistance against diseases caused by oomycetes

Oomycetes, a group of adaptive fungi, have the capacity to infect a range of economically significant plants, resulting in the widespread occurrence of diseases on a global scale (Hargreaves and van West, 2019). Despite the paucity of research examining the impact of biochar (BC) on the management of oomycetes and the minimization of infections, some evidence suggests that it may offer certain advantages. For example, the application of biochar to trees has been demonstrated to reduce disease infections and enhance plant defense mechanisms in the case of Phytophthora. Zwart and Kim (2012) demonstrated that a 5% application of pine wood BC effectively decreased root rot disease caused *Phytophthora cactorum* in *Acer rubrum* in addition to reduced infection of *Phytophthora cinnamomi* in *Quercus rubra* and by activating SAR in plants. On the other hand, Gravel *et al.*, (2013) showed that after applying softwood biochar (BC), *Pythium ultimum* causal organism of root rot, colonized more sweet pepper, lettuce, basil, and geranium plants in their rhizospheres. However, the growth of *Pythium ultimum* in the root zone did not appear to harm the plants. Furthermore, BC amendments have been shown to significantly suppress *Phytophthora* in pepper plants, with reductions reaching 91%. An increased activity of biocontrol fungi, such as

Trichoderma, *Chaetomium*, and *Aspergillus* spp., in the soil coincided with this suppression of *Phytophthora* sp. in pepper, further promoting plant health (Wang *et al.*, 2020).

Resistance against diseases caused by viral pathogens

Biochar (BC) application can considerably affect plant disease control and induction of resistance in plants. Such as the treatment of BC wood with manure applied to tomato that reduced Tomato spotted wilt virus (TSWV) infection and modification reflected in microbial and insect resistance (Bonanomi et al, 2020). Likewise, tomato mosaic virus (ToMV) symptoms were delayed and the yield of tomato fruit improved with a single application of 1.5% BC, which also increased feed efficiency (Kawanna *et al.*, 2021) (Figure 1). In field-grown tomatoes, a 3% BC amendment of maize decreased incidences of tomato leaf curl virus (TLCV) infection by 78% (Zeshan *et al.*, 2018).

Importantly, BC sugar prepared at 700 ° C is also being investigated for its ability to produce antibodies to fight SARS-CoV-2 and to destroy biological cells for the main electronic biosensor method (Valenga *et al.*, 2023). In a recent study, Elsharkawy *et al.*, (2022) evaluated the combined application of 1.5 wt% biochar and a PGPR, *Klebsiella oxytoca* (PGPR) which led to induction of resistance against potato virus Y (PVY) in tobacco and increased plant growth. Similarly, 1-20% w/w BC derived from the pruned twigs of olive has been shown to increase the number of beneficial bacteria, including Bacillus spp. and Trichoderma spp., which reduce the number of Tomato spotted wilt virus (TSWV) and Potato spindle tuber viroid (PSTVd) symptoms (Luigi *et al.*, 2022) (Figure 2). Table 5 summarizes the impact of BC applications on viral and oomycetes pathogens in various crop plants.

Table 5. Effects of BC applications on oomycetes pathogens and viruses.

Category	Pathogen	Host	Biochar Source	Application Rate	Mechanism	References
Oomycetes	*Phytophthora cinnamomi*	*Acer rubrum*	Pine wood	5% (v/v)	Stimulated the plant's defense mechanisms, boosting its resistance	(Zwart and Kim, 2012)
Oomycetes	*Pythium ultimum*	*Capsicum annuum, Lactuca sativa*	Soft wood	50% (v/v)	Increased pathogen presence in the root zone without showing symptoms	(Gravel *et al.*, 2013)
Oomycetes	*Phytophthora pepper*	*Capsicum annuum (Pepper)*	Corn stalk	13.3% (w/w)	Reduced disease severity by enhancing biocontrol fungi populations	(Wang *et al.*, 2020)
Virus	*Tomato spotted wilt virus (TSWV)*	*Solanum lycopersicum*	Wood	na	Altered bacterial and fungal populations in the soil, reducing viral infection	(Bonanomi *et al.*, 2020)
Virus	*Tomato leaf curl virus (TLCV)*	*Solanum lycopersicum*	Maize sticks	3% (w/w)	Significantly reduced disease severity	(Zeshan *et al.*, 2018)
Virus	*Tomato mosaic virus (ToMV)*	*Solanum lycopersicum*	na	1.5% (w/w)	Delayed the onset of ToMV symptoms by improving fruit nutritional status	(Kawanna *et al.*, 2021)
Virus	*Potato virus Y (PVY)*	*Solanum tuberosum*	na	1.5% (w/w)	Enhanced resistance in potato plants	(Elsharkawy *et al.*, 2022)
Virus	*Tomato spotted wilt virus (TSWV)* and *Potato spindle tuber viroid*	*Solanum lycopersicum, Solanum tuberosum*	Olive twigs	1-20% (w/w)	Increased beneficial bacteria in the soil and triggered plant resistance	(Luigi *et al.*, 2022)

MECHANISMS DEPLOYED BY BIOCHAR TO MANAGE PLANT DISEASES

Making the nutrients available to the plants

There are both unavailable and available forms of nutrients in soil, and preserving the available nutrients is the primary challenge. Major *et al.*, (2010) highlighted that biochar (BC) mixed with other manures can help minimize nutrient leaching. Schomberg *et al.*, (2012) tested nine different BCs on a farm over 127 days, finding that some BCs significantly reduced nitrogen (N) discharge losses, although overall soil N levels did not increase, primarily due to NH3 volatilization from high ash BCs. Hass *et al.*, (2012) added high-temperature chicken manure BC at various concentrations in West Virginia, observing decreases in sulfur, potash, and phosphorus, but increases in copper (Cu) and zinc (Zn) availability. Gajić and Koch (2012) suggested using low-temperature BCs with lower carbon-to-nitrogen ratios to reduce immobilization.

Interestingly, Alburquerque *et al.*, (2013) reported that the application of BC developed from olive tree pruning and wheat straw increased plant uptake of phosphorus (P), magnesium (Mg), and zinc (Zn) in acidic and nutrient-deficient soils, whereas this application reduced potassium (K) and calcium (Ca) uptake in bread wheat. Similarly, supplementing BC with nitrogen in Chernozem soil improved crop yield by up to 10% due to increased water-holding capacity in barley (Karer *et al.*, 2013). Another research demonstrated that biochars developed from poultry litter and pine chip in different combinations significantly increased microbial communities and nutrient levels in soil (Ducey *et al.*, 2015). Using poultry litter BC and pine chip biochar, they noted a significant increase in extractable nutrients like aluminum (Al), Cu, iron (Fe), and P. BC addition also enhanced nitrogen mineralization, denitrification, and nitrification processes (Cayuela *et al.*, 2013) and improved overall soil properties by adding 3% rice husk BC to sandy loam soil (Arshad *et al.*, 2022). BC also enhanced nitrogen fixation (Rondon *et al.*, 2007), with underlying mechanisms pointing to increased NH3 adsorption, improved soil aeration, and increased volatile organic matter, thereby promoting denitrification and nitrification processes (Zhang *et al.*, 2017). These reports indicate that the addition of BC in the soil or potting medium leads to increased availability of nutrients to the plants.

By promoting plant growth

A large number of reports indicate that biochar (BC) enhances the growth and development of various crop species (Ahluwalia *et al.*, 2021). Such growth improvement is mainly due to the attraction of arbuscular mycorrhizal (AM) fungi that engage in symbiotic relationships with about 80% of vascular plant species (Bonfante-Fasolo, 1987). Soil amendment with BC increases mycorrhizal fungi populations and interaction with host plants (Warnock *et al.*, 2007). Graber *et al.*, (2011) commented that BC amendments can stimulate microbial communities of plant growth-promoting rhizobacteria (PGPR) and fungi (PGPF) by providing an appropriate habitat, owing to BC's high carbon-holding capacity, which delivers vital minerals to plants.

Kammann *et al.*, (2012) observed a remarkable increase in ryegrass biomass upon peanut hull BC amendment in a German Luvisol at 50 Mg ha−1. Similarly, Major *et al.*, (2010) found that one application of BC at 20 t ha-1 to Colombian savanna soil increased maize yield by 28 to 140% over untreated controls in subsequent years. In common bean application of BC at the rate of 90 g kg-1 to low-fertility tropical soil enhanced nitrogen fixation ability of Phaseolus vulgaris, which in turn significantly increased the biomass and grain yield (Rondon *et al.*, (2007). Similarly, the amendment of the potting sandy loam soil with 30 g kg-1 rice husk BC improved plant growth parameters and physiological attributes in tomato (Arshad *et al.*, 2021; 2022). Similarly, Rondon *et al.*, (2005) found increased bean biomass with BC applied at 60 Mg ha-1. Lehmann *et al.*, (2007b) reported that crops responded positively to BC additions up to 50 MgC/ha, though very high applications could reduce growth. Very recently, BC was used as a career material for seed priming to boost plant growth in bread wheat (Jabran *et al.*, 2024).

By accumulating beneficial microbes in the rhizosphere

Soil is the most diverse habitat for land microbes and specifically plant rhizosphere is considered as one of the most diverse ecosystems on the earth planet (Ali *et al.*, 2017, Eskov *et al.*, 2021). Biochar amendments are a key process that is used to engineer rhizosphere microbiomes in different plant species (Ali *et al.*, 2017). Different studies have shown the impact of biochar application on the microbial status of the soil. Biochar mainly provides microbial communities with a porous structure of the soil that acts as a safe haven for different microorganisms, protecting them from pathogens, parasites, and other non-living factors (Qi *et al.*, 2022). However, to date, there is limited information on how BC aids various microbes and how they become accustomed to life in the BC-amended environment. There are several reports from the literature that show improved microbial diversity in the soil after the application of BC. For instance, a recent report displayed that the addition of BC to soil significantly impacts the development of beneficial microbial communities, enhancing plant growth and development (Li *et al.*, 2020). This kind of alteration may be due to chemical transformations in nutrients and pH levels during BC decomposition, leading to a decreased susceptibility to plant diseases and an increase in plant growth attributes. BC may promote microbial communities in the rhizosphere through gradual nutrient release and absorption of toxic compounds in the micropores present in the BC (Kocsis *et al.*, 2018). Similarly, some studies showed how BC and soil microbes are interconnected. For example, Watzinger *et al.* (2014) demonstrated that wheat straw BC improves the overall microbial community in temperate soils regardless of changes in carbon and physio-chemical attributes of soil. BC developed from wheat straw and peanut shells increased the bacterial populations in fresh soil (Du, 2018).

However, recently Domene *et al.*, (2021) reported that the fungal microbes present in the soil due to BC application favor the establishment of more fungivorous and bacterivorous nematode species. In another study, it was found that there was no important increase in bacterivore nematodes, showing that bacteria-eating organisms did not react much to crop leftovers (Dupont *et al.*, 2009). Biochar affects soil microbial populations and biodiversity, with its tiny pores providing a safe place for many microorganisms. Adding biochar to soil improves the partnerships between plants and mycorrhizae (Vahede *et al.*, 2021). Brtnicky and colleagues (2021) reported that BC application leads to lower concentrations of toxic compounds conditioned by microbial biomass activities in sandy soil. Ren *et al.*, (2018) demonstrated that soil type and BC type affect soil microbial diversity. Zhu *et al.* (2017) reported that incorporating BC into soil enhances essential nutrients (e.g., dissolved Ca, K, P, and organic matter), adsorbs toxic compounds, improves soil pH, and influences microbial activity. Very recently, Verma *et al.* (2023) added 15% wheat straw BC into the soil and reported that it enhances fungal diversity in the soil.

Upregulation of resistance genes

Plants have a big reservoir of genes involved in diverse resistance responses against different plant pathogens (Rasul *et al.*, 2019). BC application has shown its ability to induce different defense-related genes in crop plants (Arshad *et al.*, 2021). BC amendments have been linked with the upregulation of disease-resistance genes, enhancing plant immunity. Foliar sprays of BC were associated with enhanced expression of defense-related genes in strawberry plants, such as FaPR1, Falp2, Fra a3, Falox, and FaWRKY1, providing additional resistance against *Botrytis cinerea* and *Podosphaera aphanis* (Harel *et al.*, 2012). The use of potting medium containing 1.2% BC derived from oak wood has been shown to trigger ethylene signaling pathways and H_2O_2 generation in rice plants, thus enhancing the expression of various ethylene-related genes, namely OsERF1 and OsEBP89, thereby providing resistance against *Meloidogyne graminicola* (Huang *et al.*, 2015).

The application of citrus wood-based BC amendments, formulated at concentrations of 1-5%, has been shown to act as a SAR inducer in tomato and pepper plants, thus mitigating infections from both necrotrophic *Botrytis cinerea* and biotrophic *Leveillula taurica* fungal pathogens (Elad *et al.*, 2010). Arshad *et al.* (2021), utilized rice husks and wheat straw BC at different concentrations (3–5%) in tomato to manage RKNs in tomato and displayed that these BCs upregulate defense-related genes like JERF3 and PR-1 thus enhancing SAR-based resistance against RKNs. These findings open up a new avenue to potentiate BC applications as a possible sustainable tool for managing plant diseases and enhancing crop resilience.

UTILIZATION OF BIOCHAR FOR CONTROLLING INSECT PESTS

Biochar enhances soil health via improvements in physical, chemical, and biological properties (Singh *et al.*, 2022). Such improvements will encourage the proliferation of beneficial microorganisms to provide competition or inhibition towards detrimental insecticidal pests. Biochar can lead to a more systemic defense in plants, thus making plants more resistant to insect attacks. This systemic defense response from the plants takes place through the activation of stress-related hormones like JA which alter the metabolic processes of the plants culminating in enhanced plant resistance against insect pests (Upadhyay *et al.*, 2024). Similarly, the presence of pores in the BC structure provides a healthy habitat for microbes that are antagonistic to insect pests (Lu *et al.*, 2018). Moreover, BC addition leads to modifications in the soil environment making it unfit for insect pest survival and reproduction and lower insect populations (Upadhyay *et al.*, 2024). Table 6 summarizes the impact of BC applications on various insect pests in different crop plants.

Biochar application also has a good impact on environmental cleanliness. BC amendments, on one side, lower the use of chemical pesticides, and on the other side, help to control pesticide-resistant insect populations (Elad *et al.*, 2010). Biochar improves nutrient retention in the soil for a longer time and fosters plant growth which supports the idea that healthier plants are generally more resistant to insect damage (Poveda *et al.*, 2021) (Table 6). Some insect pests can be directly killed by biochar by contact or ingestion in specific situations (Rice, 2022).

Table 6. Effects of BC applications on insect pests infesting various crops.

Insect species	Host	Biochar Source	Application rate	Mechanism	References
Sogatella furcifera	Rice	Deciduous trees, dolomite, and molasses	10% (w/w)	Accumulation of JA in leaves	Waqas *et al.* 2018
Polyphagotarsonemus latus	Pepper	Citrus wood	1 & 3% (w/w)	SAR	Elad *et al.* 2010
Rhyzopertha dominica	Stored grains	Rice husk	5% w/w	Alters soil conditions, induces systemic plant responses	Hassan *et al.*, 2022
Oryzaephilus surinamensis	Stored grains	Sugarcane bagasse	5% w/w	Changes soil micro-biota, influences pathogen motility	Hassan *et al.*, 2022
Tribolium castaneum	Stored grains	Leucaena tree residues	5% w/w	Induces plant systemic defenses, suppresses nematode and insect pests	Hassan *et al.*, 2022
Sitophilus oryzae	Stored grains	Chicken manure	5% w/w	Enhances nutrient status, improves plant response to soil pathogens	Hassan *et al.*, 2022
Amrasca biguttula *Bemisia tabaci* *Leucinodes orbonalis*	Brinjal	Rice husk	Different concentrations	Rice husk biochar reduces insect infestation on brinjal plants by improving Si uptake	Bakhat *et al.*, 2021
Sitobion avenae	Wheat	Corn, Wheat & Rice straw	3% and 5%	Detrimental effects on the reproductive potential	Chen *et al.*, 2019a
Cnaphalocrocis medinalis	Rice	Wheat straw	1.5%, 3% or 5%	Impairment of *C. medinalis* development	Chen *et al.*, 2019b
Sitobion avenae & Laodelphax striatellus	Wheat & Rice	Corn, Wheat & Rice straw	1.5%, 3%, or 5%	Limit stylet penetration activities	Chen *et al.*, 2019c
Laodelphax striatellus	Rice	Corn, Wheat & Rice	30 g/kg, 50 g/kg	Negative impact on fecundity of L. *striatellus*	Fu *et al.*, 2018
Nilaparvata lugens	Rice	Wheat straw	200 g/kg	Negative impacts on the development and reproduction	Hou *et al.*, 2015
Spodoptera frugiperda	Maize	Rice husk	4t/ha	Negatively influenced the infestation	Pavani *et al.*, 2023

These diverse and additive roles of BC thus explain its potential in integrated pest management (IPM) strategies for sustainable agriculture paving the way towards minimizing the use of chemical inputs while promoting stress tolerance in plants (Galli *et al.*, 2024). Moreover, BC amendment in the soil and/or potting medium provides habitats for beneficial microorganisms that can stand against attacking these pests (Elad *et al.*, 2010). (Figure 2).

Biochar can act as a natural insecticide when integrated into agricultural systems. Indeed, as we'll discuss next, there are a multitude of pest control options and biochar is relevant to many. For example, biochar is highly effective in controlling the pest populations that appear in specific conditions within agricultural systems. Specific examples of these applications might include the effective treatment of the rice weevil in stored grains as shown in such studies mentioned here (Upadhyay *et al.*, 2024). In this case, by altering the soil environment conditions may be less favorable for pests to spread and consume the stored grain. Another example is when the southern corn rootworm is controlled by the application of forestry waste biochar (primarily for the reasons stated earlier: improved soil health allows for plant health to improve which enables the plant to stave off pests) (Tikoria, *et al.*, 2023).

In another instance, the application of biochar has been shown to effectively control the damage caused by the western corn rootworm: by creating healthier soil and a more optimal microbial community, the environment for the pest is not as favorable. Furthermore, the application of biochar has helped to control Colorado potato beetle populations (Kamali, *et al.*, 2024). Plant health is considered because biochar is integrated into the root zone, after which plant vigor would be expected to increase. This phenomenon deters insects from feeding on the plant foliage making it less appealing to the potato beetle (Kamali, *et al.*, 2024). Research reports have found biochar suppresses pest populations (cabbage loopers) by improving the soil microbial community and plant vigor: the results can be found in this analysis by Wakefield (2024). Another example includes evidence that biochar reduces the infestation of green peach aphids by altering the soil environment and the chemistry of the plant (Upadhyay *et al.*, 2024).

CONCLUSIONS

This literature review concludes that BC application has significantly changed the dynamics of agricultural systems. Biochar application has been equally important for managing biotic (insects, nematodes, fungi, viruses, and bacteria) diseases and abiotic stresses. Biochar uses different mechanisms in managing biotic and abiotic stresses ranging from nutrient management to microbial interactions which are beneficial for crop plants. Moreover, BC application significantly influences the plant-water relations to alleviate the abiotic stresses. In short, BC applications may lead world agriculture towards sustainability and ultimately to food security for the ever-increasing world population.

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