Effects of Biochar on Different Plant Diseases

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Soilborne pathogens and pests in agroecosystems are serious problems that limit crop yields. Apart from its direct positive effects on plant growth and promotion, biochar appears to be a new and promising tool for controlling several plant diseases and pests.

plant disease   sustainable control   organic amendment   biochar

1. Introduction

Biochar is a heterogeneous material produced by pyrolysis, a thermal process carried out at temperatures between 200 °C and >900 °C and under limited oxygen availability [1].

Biochar differs from charcoal because it can be used as an efficient soil amendment [2]. The elemental composition of biochar varies depending on the biomass feedstock from which it is produced and the characteristics of the pyrolysis process [3]. Biochar is characterized by a high C-to-N ratio, even exceeding 100, and a high content of organic aromatic carbon. Thanks to these properties, biochar is resistant to microbial degradation and its estimated average residence time in the soil varies from centuries to millennia [4]. The use of biochar in agriculture is not new, but dates back to ancient times when the pre-Columbian people of Amazonia developed the so-called “terra preta” or “dark earth” soils through repeated cycles of fire and cultivation, i.e., the slash-and-char system [5]. In this way, nutrient-poor and highly weathered acidic soils were transformed into a fertile substrate that could sustain indigenous populations [6]. Several studies have confirmed the positive interactions of biochar with soil, such as liming effect [7], increasing water retention capacity [8], and the ability to adsorb phytotoxic organic molecules [9]. The changes induced by biochar may well affect nutrient cycling [10] and soil structure [11], thus indirectly affecting plant growth [12], and also soil organic matter cycling [13][14][15]. In addition, biochar has been shown to stimulate the activity of beneficial microbes [12] and suppress soilborne pathogens [16]. The beneficial effects of biochar are often explained by its porosity and sorption capacity [17], redox properties [18][19], and influence on soil structure [20][21].

Soilborne plant pathogens in agroecosystems pose serious problems for agriculture and crop yields. Organic amendments have already been proposed to reduce the incidence of diseases caused by soilborne pathogens [22]. In this context, biochar seems to be a promising tool for controlling various plant pathogens. Indeed, an important application of biochar is its use as an agent for the effective control of plant diseases. Bonanomi et al. [16] reported that biochar effectively suppresses diseases caused by airborne and soilborne plant pathogens such as *Fusarium oxysporum* f. sp. *asparagi*, *F. oxysporum* f. sp. *radicis-lycopersici*, *F. proliferatum*, *Pythium aphanidermatum*, *Phytophthora cactorum*, *P. cinnamomi*, and *Rhizoctonia solani*. Previously, both Elad ad et al. [23] and Harel et al.

[24] reported that biochar produced from wood and greenhouse wastes significantly reduced the incidence of powdery mildew caused by *Leveillula taurica* on *Lycopersicon esculentum* and *Podosphaera aphanis* on *Fragaria x ananassa*, respectively. Five main mechanisms have been proposed to explain disease suppression by biochar: (i) induction of systemic resistance in host plants; (ii) enhanced abundance and activity of beneficial microbes, including mycorrhizal fungi; (iii) alteration of soil quality in terms of nutrient availability and abiotic conditions, such as liming effect; (iv) direct fungitoxic effect of biochar; (v) sorption of allelopathic phytotoxic compounds that can directly damage plant roots and thus promote pathogen infestation. With the aim of developing more ecologically sustainable agriculture, the possibility of using biochar to defend against pathogens has increased in prominence in recent years in light of previous studies.

Apart from its direct positive effects on plant growth and promotion [25], biochar appears to be a new and promising tool for controlling several plant diseases and pests, with most case studies reporting positive suppressive effects. Studies investigating the effects of different types of biochar on plants are summarized below and subdivided by pathogen type.

2. Fungi and Oomycetes

Fungi and oomycetes can be divided into two broad groups: obligate parasites, which depend entirely on living host plant tissue for nutrition and reproduction, and facultative parasites, which cause significant damage to plants but can also live as saprophytes on plant debris and organic material [26]. Pathogens that attack aboveground plant organs are referred to as foliar pathogens, while those that attack the root system and reside primarily in the soil are referred to as soilborne pathogens [27]. The potential benefits of biochar in suppressing diseases caused by pathogenic soilborne fungi have been demonstrated in several studies (**Table 1**) For example, Akhter et al. [28] evaluated the response of *Fusarium oxysporum* f. sp. *lycopersici* chlamydospores on tomato plants grown in soil enriched with biochar and compost and found that the amended soil had great potential to suppress chlamydospore infectivity and reduce pathogen-related physiological stress in tomato plants. Moreover, Akanmu et al. [29] demonstrated the efficacy of biochar in controlling *Fusarium* ear rot in maize. Similar results were reported by Wu et al. [30], who found that soil treatment with biochar resulted in a reduction in the abundance of *Fusarium oxysporum* and a reduction in the virulence of the fungus on *Radix pseudostellariae* plants. The suppressive effect of biochar was also tested against airborne plant pathogens. For example, Rasool et al. [31] studied the effect of green waste biochar (GWB) and wood biochar (WB) together with compost and plant-growth-promoting rhizobacteria (PGPR; *Bacillus subtilis*) on the physiology of tomato (*Solanum lycopersicum*) and the development of *Alternaria solani*, and showed for the first time that disease suppression was strongest (up to 80%) in the presence of *B. subtilis* in the GWB-containing substrate. In addition, De Tender et al. [32] showed how biochar treatments can improve the disease resistance of strawberry plants to the airborne fungal pathogen *Botrytis cinerea* by recruiting microbes from the rhizosphere. On the other hand, several studies have also investigated the ability of biochar to suppress oomycetes. Wang et al. [33] investigated the suppression of *Phytophthora pepper* blight in a pot experiment as a function of time after biochar application. Biochar treatment effectively inhibited pathogen growth, reduced disease by up to 91%, and significantly increased the incidence of potential biocontrol fungi. However, a few case studies have shown a negative effect of biochar on disease control. For example, Copley et al. [34] showed that maple bark biochar increased soybean susceptibility to diseases caused by *Rhizoctonia solani*. At lower concentrations (1% and 3%), biochar was ineffective against the disease, but at a 5% application rate, biochar treatment showed a significant increase in disease severity caused by *R. solani.* The authors provide compelling evidence that biochar is associated with the downregulation of a number of genes related to primary and secondary plant metabolism, such as genes involved in amino acid metabolism, cell wall plasticity, and the tricarboxylic acid (TCA) cycle, which likely facilitated entry points, resulting in higher susceptibility to *R. solani*.

Table 1. List of experimental studies examples that applied biochar as a soil amendment to control plant diseases caused by airborne (A) and soilborne fungal (SB) pathogens. Pathogen, host plant, biochar feedstock type, response level, and reference are reported for each study.

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
Fusarium oxysporum f. sp. *radicis lycopersici* (SB)	*Solanum lycopersicum*	Wood (1–3%)	Medium–high	[35]
Alternaria solani (A)	*Solanum lycopersicum*	Wood—green wastes (3–6%)	high	[31]
Fusarium oxysporum f. sp. *radicis lycopersici* (SB)	*Solanum lycopersicum*	Wood—wastes (1–3%)	Medium–high	[35]
Fusarium oxysporum f. sp. *radicis lycopersici* (SB)	*Solanum lycopersicum*	Wood—wastes (3%)	high	[28]
Botrytis cinerea (A)	*Solanum lycopersicum*	Wood (1%)	high	[36]
Fusarium oxysporum f. sp. *radicis lycopersici* (SB)	*Solanum lycopersicum*	Green house wastes (1–3%)	high	[37]
Alternaria solani (A)	*Solanum lycopersicum*	Wood—green wastes (3–6%)	Medium–low	[31]
Fusarium oxysporum f. sp. *lycopersici* (SB)	*Solanum lycopersicum*	Wood (0.5–3%)	Medium–high	[35]
Fusarium verticillioides (SB)	*Zea mays*	Wastes (1–3%)	Medium	[29]

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
Fusarium oxysporum (SB)	*Radix pseudostellariae*	Hull (3%)	High	[30]
Botrytis cinerea (A)	*Fragaria x ananassa*	Organic matter (1–3%)	High	[32]
Fusarium spp. (SB)	*Panax notoginseng*	Wood (8 g L^{-1})	Medium	[38]
Magnaporthe oryzae (A)	*Lolium perenne* L.	Straw (0.22–1%)	Medium–high	[39]
Fusarium solani (SB)	*Malus*	Husk (5–80 g kg^{-1})	Medium	[39]
F.oxysporum f. sp. *radicis-lycopersici* (SB), *Botrytis cinerea* (A), *Fusarium oxysporum* (SB), *Ganodema lucidum* (SB), *Penicillium italicum* (A), *Rhizoctonia solani* (SB), *Sclerotinia sclerotiorum* (SB)	*Solanum lycopersicum*	Medicago-Mays—organic wastes (5%)	High	[40]
Verticillium dahliae (SB)	*Solanum melongena*	Husk (10 t/ha biochar)	High	[41]
Phyllactinia corylea (A), *Pseudocercospora mori* (A)	*Morus alba*	Husk	Medium	[42]
Leveillula taurica (A)	*Capiscum annum* L.	Green house wastes—wood	High	[43]
Fusarium oxysporum (SB), *Fusarium oxysporum* f.sp. *asparagi* (SB), *Fusarium proliferatum* (SB)	*Asparagus officinalis* L.	Wood (10%)	Medium–high	[44]
Rhizoctonia solani (SB)	*Glycine max*	Wood (1–5%)	Negative effect	[34]
Fusarium oxysporum f. sp. *radicis-lycopersici* (SB), *Fusarium oxysporum* (SB), *Rhizoctonia solani* (SB), *Sclerotinia sclerotiorum* (SB), *Macrophomina phaseolina* (SB), *Sclerotium cepivorum* (SB), *Sclerotium rolfsii* (SB)	*Jatropha curcas* L.	Sewage sludge (0.2–1%)	Medium–high	[45]

3. Bacteria

Regarding pathogenic bacteria in soil, a suppressive capacity of biochar was reported for *Ralstonia solanacearum* [46], *Kosakonia sacchari* [30], *Agrobacterium tumefaciens* [40], and *Streptomyces scabies* [47]. Regarding airborne pathogenic bacteria, Bonanomi et al. [40] reported a high efficacy of biochar against *Pseudomonas syringae* and

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
Fusarium torulosum (SB), *Fusarium solani* (SB)	*Panax ginseng*	Straw (1%)	High	[46]

ar on the gated the [46] eir results har while mino acid composition in the rhizosphere. Furthermore, Gu et al. [48] investigated the efficacy of applying 3% wood biochar to suppress bacterial wilt of tomato caused by *R. solanacearum.* Specifically, the application of fine biochar significantly reduced the incidence of bacterial wilt by 20% and reduced pathogen mobility and rhizosphere colonization.

Table 2. List of experimental studies examples that applied biochar as a soil amendment to control plant diseases caused by airborne (A) and soilborne (SB) bacterial plant pathogens. Pathogen, host plant, biochar feedstock type, response level, and reference are reported for each study.

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
Ralstonia solanacearum (SB)	*Solanum lycopersicum*	Straw (2%)	High	[46]
Ralstonia solanacearum (SB)	*Solanum lycopersicum*	Straw (2%)	High	[49]
Ralstonia solanacearum (SB)	*Solanum lycopersicum*	Straw (2%)	Medium–high	[48]
Kosakonia sacchari (SB)	*Radix pseudostellariae*	Hull (3%)	High	[30]
Agrobacterium tumefaciens (SB)	*Lactuca sativa*	Medicago, wood, organic wastes, maize (5%)	High	[40]
Pseudomonas syringae (A)	*Solanum lycopersicum*	Medicago, wood, organic wastes, maize (5%)	High	[40]
Pseudomonas viridiflava (A)	*Solanum lycopersicum*	Medicago, wood, organic wastes, maize (5%)	High	[40]
Lysobacter sp. (SB)	*Solanum lycopersicum*	Medicago, wood, organic wastes, maize (5%)	High	[40]
Ralstonia solanacearum (SB)	*Nicotiana Tabacum*	Hull (7.5–45 ton/ ha)	High	[50]
Ralstonia solanacearum (SB)	*Solanum lycopersicum*	Wood (3%)	High	[48]
Streptomyces scabies	*Solanum*	Different agricultural wastes	Medium	[47]

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
(SB)	*tuberosum*	(0.5 ton/ha)		

[51][52][53] However, the few studies available show great potential to protect plants from phytopathogenic viruses using biochar.

Table 3. List of experimental studies that applied biochar as a soil amendment to control plant diseases caused by viral plant pathogens. Pathogen, host plant, biochar feedstock type, response level, and reference are reported for each study.

Pathogen	Host Plant	Biochar Type and Application Rate	Response	References
Curl virus (SB)	*Solanum lycopersicum*	Maize (1–3%)	High	[53]
Tomato Mosaic virus (SB)	*Solanum lycopersicum*	Husk (0.5–1.5%)	Medium	[52]
Tomato spotted wilt virus (TSWV) (SB)	*Solanum lycopersicum*	Wood	High	[51]

Specifically, Zeshan et al. [53] tested the efficacy of biochar from maize at 1%, 2%, and 3% concentrations on tomato (*Solanum lycopersicum*) plants infected with leaf curl virus. After biochar soil treatment, disease severity was found to be 22%, which was significantly lower than that of the control (40%). Kawanna et al. [52] reported a reduction in tomato mosaic virus incidence after the application of 1% and 1.5% biochar obtained from rice husk material. The rates of infection and disease severity were reduced by 50% and 37% following treatments with 1.5% and 1% biochar in the soil, respectively. Finally, Bonanomi et al. [51] studied the suppressive effect of biochar against Tomato spotted wilt virus in tomato plants. Plants grown in soils treated with biochar had a lower incidence of the disease (<40%) than those grown in soils treated with mineral fertilizer and fumigation (>80%). In their study, the authors noted a significant change in soil microbial community and structure after biochar application, and speculated that induction of resistance might be the cause of disease suppression.

5. Nematodes and Insects

Arshad et al. [54] tested biochar derived from rice husks in combination with biological control agents (BCAs) such as *B. subtilis* and *Trichoderma harzianum* against *Meloidogyne incognita* in tomato (*S. lycopersicum*). The results indicate that applying 3% biochar with BCAs effectively controlled root-knot nematode, improved overall plant biomass, and activated genes related to tomato plant defense. Similarly, Oche Eche and Okafor [55] showed that biochar from gum arabic, bush mango, and locust bean is a promising control agent for *M. incognita*. In addition, Marra et al. [56] demonstrated that biochar from olive mill waste produced complete inhibition of the root-knot nematode *M. incognita* due to the presence of several compounds in the biochar, mainly fatty acids and phenols, which are known to be among the phytochemical compounds that exhibit nematicidal effects.

Regarding insects, Chen et al. [50] investigated the effect of biochar on the development and reproductive performance of *Cnaphalocrocis medinalis* on rice and examined the population size of *C. medinalis*, showing that biochar can affect its development and has negative effects on its population. Furthermore, Edenborn et al. [57] studied the effects of modified hardwood biochar with different types of compost tea and microbial enrichment from vermicompost on eggplant (*S. melongena* var. Rosa Bianca) growth and flea beetle (*Epitrix fuscula*) damage. The authors found that adding biochar did not improve resistance to insect damage.

6. Parasitic Plants

Parasitic plants are a taxonomically diverse group of angiosperms that are partially or completely dependent on host plants for carbon, nutrients, and water, which they obtain by attaching to the roots or shoots of the host. Parasitism often results in severely impaired host plant performance, leading to changes in the competitive relationships between host and nonhost plants and a cascade of effects on community structure and diversity, vegetation cycling, and zonation [58]. Research revealed two case studies of use of biochar against parasitic plants. Eizenberg et al. [59] conducted experiments in pots of tomato (*S. lycopersicum*) infested with *Phelipanche aegyptiaca* (Egyptian broomrape) using biochar prepared from greenhouse pepper plant waste. The addition of biochar resulted in reduced infestation of the tomato plants, mainly by reducing germination of *P. aegyptiaca* seeds due to adsorption to the biochar of stimulatory molecules, i.e., strigolactones. On the other hand, Saudy et al. [60] conducted the first field experiment investigating the use of biochar for control of broomrape weed (*Orobanche crenata*) in two faba bean cultivars. Biochar prepared from dry plant waste of *Casuarina equisetifolia* was associated with significant reduction of broomrape infestation. The authors suggested that the addition of biochar might represent a barrier handicapping the accession of faba bean root stimulants to broomrape seeds, preventing their germination. Moreover, application of biochar could change the rhizospheric environment to one unsuitable for broomrape seed germination, or could even cause damage to germinated seeds. These studies prove that biochar can also reduce infestations of parasitic weeds in important crops, suggesting new treatment strategies for this type of pest and highlighting the economic feasibility of using biochar.

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