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Review Article

Plant Disease Management through Bio-Char: A Review

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Bio-char; Pyrolysis; Induced resistance; Fusarium

A B S T R A C T

Bio-char, a carbonaceous organic byproduct of pyrolysis which have shown a great significance in inducing the resistance within the tomato plants by stimulating the activity of PR-proteins and phenolic compounds against the pathogen *Fusarium oxysporum* f. sp. *lycopersici* (a soil borne plant pathogen). Bio-char is added in the soil as an amendment with different concentrations viz., 1-5 percent to induce resistance into plants. Bio-char not only induces the resistance within the plants but also increases the yield of the plants and reclaim the nutrient ability of the soils. Bio-char application in the soil proved as an effective measure in order to induce resistance when compare with various other chemicals (inorganic) responsible for the induction of the disease resistance within the plant system.

Introduction

The Plant system has various defense mechanisms in order to resist the attack of various disease causing pathogens. These mechanisms include physiological barriers like cuticle layers, waxy layers, secretions of the various toxins at the surface of the leaves or the stem; mechanisms at metabolic or cellular levels like activation of various PR proteins or various other chemicals within the plant cells which will activate the defense activities including hypersensitivity or SAR or ISR approaches. Through last few years the concept of induced resistance has been widely popular in order to induce the resistance within the plants by artificial means by various modes; use of various chemicals, bio-agents or organic amendments at different rates at different stages of growth with in the plants. Plant protection plays a general and significant role in meeting the demands of the population for food and other requirements (Strange and Scott, 2005). The losses caused by the diseases attack has been ranges upto 16% every year (Teng and Krupa, 1980; Oerke, 2006). The crop losses due to the attack of the pests and diseases have ben occurred either directly (yield and cost losses) and indirectly (marketing and exporting) (Zadoks, 1967). Lossby plant pathogens due to the various diseases affects production, importation, storage, physical and economic access to the food (Zadoks, 1967). In the 20th century most of the research works in agriculture is based on the increase in production of the crops so as to fulfill the supply to world population (Smil, 2000). The disease control is always remains a challenging task with increasing complexities with every new invention or research in the agriculture for disease resistance within the plants (Brown, 2011; FAO, 2011). So there is always a need of new methods and concepts in the disease resistance to be developed to reduce their harmful effects on the plants (McRoberts *et al.*, 2011). The farmers in India are not only facing the disease problems on their crops but meanwhile there are various other problems also which have been taking a greater part of the farmers economy, includes; attack of various insects and pests, availability of seeds and fertilizers on time, supply of irrigation water, marketing of the agriculture production and many more other problems are there (McRoberts *et al.*, 2011; Savary, 1994). So there is a need of a such kind of system or a concept or a research which will benefit the farmers not only on the basis of the diseases to the crop but also reduce their invest on the various farm inputs and increase in the production of the crop along with the increase in the economy of the farmers which leads to a healthy economic life of the farmers.

The use of various chemical treatments no doubt helps the farmers to control the diseases but at the same time they cause huge toxic or ill effects on the soil health and environment. The chemicals being used in agriculture for diseases treatment and other purposes have been also inducing the resistance in the various pathogens against their activity which have been creating serious and devastating problems in agriculture sectors. This has been occurred due to increased consumption of agro-chemicals without any restrictions (www.davidmoore.org.uk). Although various legislations and various other legal authorities have been in the act according to the Indian Constitutions. These are Insecticide Act, 1968 framed under the Insecticide Rules, 1971; Environment Protection Act, 1986; Prevention of food adulteration act, 1954; Factories Act, 1948 (Singh D.K, 2007). Function of these acts is to protect the environment from toxicities of chemicals induced in the agriculture and limits their consumptions and to check their quality standards and their production parameters. Beside these acts consumption of chemicals have been increasing day by day in agriculture sector, therefore there is a need of strict legislations to implement in the real sense as to protect our soils from toxicities.

There is a strong need to create a diversion from the conventional agriculture to a new approach as to create a well-being of the soils and the human health. For this purpose various organic amendments have been induced in agriculture but their application limited over a small rates. Therefore there is a need to create a kind of awareness among farmers for the organic amendments which will provide same benefits as chemicals could have been provided. Bio-char is one amongst great approach can be used to achieve that vary purpose. It is being introduced as a new and advanced approach for induction of disease resistance in plants against various soil borne diseases (Lehmann *et al.*, 2007).

What is Bio-char?

Bio-char is a kind of charcoal, supplemented as a soil amendment considered as a heterogenous material generated or produced by pyrolysis, which is a thermal combustion occurs at the temperature varies from 200°C to 900°C and in the limited oxygen supply, from a great variety of organic materials which includes crop wastes or residues (Yuan *et al.,* 2011), woodchips (Spokas and Reicosky, 2009), urban or municipal-wastes (Mitchell *et al.*, 2013), slugde from sewage

(Mendez *et al.,* 2012), manures and other organic amendments (Uzoma *et al.*, 2011), and from bones of animals (Vassilev *et al.*, 2013). Bio-char is a solid, stable, carbon rich product and have been naturally prepared in soil from thousands of years. Since it has been prepared from the various organic feed stocks, the chemical and physical properties of Bio-char has not been generalized. Every Bio-char prepared from different feedstock's show variation in their chemical and physical properties. It is a highly carbonaceous organic amendment been used in the agriculture for inducing resistance in the plants against various soil borne pathogens by activating the various defense activities within the plants (Lehmann *et al.*, 2007). Bio-char is being used various crop against various disease causing pathogens like;

Fusarium (Elmer *et al.*, 2011)

Botrytis (Harel *et al.*, 2012)

Phytophthora (Shoaf *et al.,* 2016)

Rhizoctonia (Jaiswal *et al.,* 2015)

Bio-char against *Fusarium* spp.

Fusarium belongs to the phylum Ascomycota and are of great importance because it sustains various species itself which causes various type of diseases in variety of plant species (Nelson *et al.*, 1981). The colonies of the *Fusarium* spp. in the media appears to be cottony with densely grown white hyphae. This fungi produces the various types of pigments with different colors which are very helpful for their identification. These colors may be white-pink, salmon pink, purple and carmine red (Bullerman, 2003). The *Fusarium* spp. produces the septate and sickle shaped conidia mostly known as macroconidia (fusiform shape) and microconidia (pyriform shape). The various species have been classified based upon great host specificity and each species possess a wide variety of the virulence and pathogenicity to different species of plants (Hansen and Snyder, 1940). The sexual stages have been found in some of the *Fusarium* species; the species having sexual or teleomorphic stages have been described under the phylum Ascomycota, order Hypocreales and various genera like *Nectaria* and *Gibberella* (Samuels *et al.*, 2001). *Fusarium* causes diseases to the various major plant species which are economically very important most of them are soil borne.

The *Fusarium* species like *F. avenaceum*, *F. graminearum*, *F. culmorum* and *F. poae* causes diseases like root rot, brown foot rot, glume, blight canker etc. in the crops of the oats, rye, barley and wheat. (Marcio *et al.*, 2013). The *Fusarium* also causes the diseases in rice and maize crops causing sheath rot and pink ear rot respectively. Also causes diseases in number of economically important horticultural crops including the banana (panama wilt), tomato (wilt), wilt of chilly, wilt of brinjal, mango malformation etc. The most frequent diseases caused by the two species of the *Fusarium* i.e. *solani*; (causes upto 50% of the diseases and *oxysporum*; causing approximately 20% of diseases (Chris *et al.*, 2017). The spores of this fungi can survive upto 16 years in the soil (Marcio *et al.*, 2013).

The *Fusarium* spp. have also been more significant due to the production of the various secondary metabolites or mycotoxins which are biologically active. These are fusaric acid, fusarins, gibberellin, moniliformin, zearalenone, trichothecenes and fumonisims (Proctor and Desjardins, 1999; Nijs *et al.,* 1996). Gibberellin has been widely used for enhancing the growth of the various horticultural crops to increase their production (Tudzynski. 2002).

Although various chemicals have been used to control this fungi in the plants or to reduce their growth in the soils. These chemicals were Tebuconazole; used as the seed dressing or seed coating to avoid the *Fusarium* fungi from penetrating into the seeds (Massino *et al.,* 2006), Carbendazim; used as the foliar application on the infected crops (Weitang *et al.,* 2004), Thiram; used as seed coating (Weitang *et al.,* 2004) etc. Numerous biological treatments have also been initiated and used to control this were *Trichoderma harziarum* (Datnoff *et al.,* 1995; Sivan *et al.,* 1986); *Glomus intraradices* (Datnoff *et al.,* 1995); *Pseudomonas florescens* (Jos *et al.,* 1995; Niemann *et al.,* 1991); A new approach i.e., Bio-char has been proved to be very effective in the control of the *Fusarium* spp. under controlled as well as field conditions (Lehmann *et al.,* 2007; Elmer *et al.,* 2011). The application of the Bio-char in the greenhouse in the plants of the asparagus @ 1.5 to 3.0% w/w in the field soils reduces the incidence of root lesion disease caused by *Fusarium oxysporum* f. sp. *asparagi* and *Fusarium proliferatum*. It also increases the root weight of the asparagus plants (Elmer *et al.,* 2011). It was also observed that growth rate of *Fusarium* spp. in the soils treated with Bio-char has been reduced to the 50% as compared to the soils not treated with Bio-char where the growth of the pathogen is 93 percent (Matsubra *et al.,* 2002). The Bio-char application in the soils reduced the growth of the chlamydospores within the soil which reduces the disease incidence caused by the *Fusarium* spp. (Adnan *et al.,* 2016). In tomato plants it has been seen that the Bio-char application reduces the disease caused by the *Fusarium oxysporum* f.sp. *lycopersici* (Martinez *et al.,* 2015). The application of the Bio-char also seems to increase the production of the tomato plants upto 64% as compare to the control tomato plants (Mustafa *et al.,* 2010). There are the cases too where hormesis effect (low dose reduces the diseases incidence and high dose increase the severity) has been observed (Jaiswal *et al.,* 2014). Application of Bio-char has increased the incidence of *Fusarium* spp. when it was used @ 3% (Akhtar *et al.,* 2015).

Bio-char against *Botrytis cinerea*

Botrytis cinerea causes grey mould, a post-harvest disease (Romanazzi, 2014) in about 200 plant species (Lynne Body, 2016). This fungi belongs to the Ascomycota phylum and Sclerothiniaceae family and appears as grey fluffy mycelium on surface of the infected plant parts (Lynne Boddy, 2016). It produces a large quantity asexual spores which will then germinate on the plant surface develop appresoria and penetration pegs through which they penetrate into the plant's cuticle layers. *Botrytis* produces various chemical molecules into host plants that causes death of tissues then plants. These chemicals are oxalic acid, botrydial and HST's (Lynee Boddy, 2016). This fungi triggers the hypersensitivity responses within the plants but they do not cause any harm since *Botrytis* is a necrotroph by nutrition so, inspite of harming the pathogen it provides a benefit for the widespread of the fungi (Lynne, 2016). It also has been a major disease of various horticultural crops (grapes and pomegranate) which causes pre harvest grey mold disease on the surface of fruits and leaves (Elmer *et al.,* 2017).

The teleomorphic stage of *Botrytis cinerea* is *Botryotina fuckeliana*, an air borne pathogen (Williamson *et al.,* 2007). The most favorable atmospheric conditions preferred by this fungi stands in temperate and subtropical regions. It causes the diseases in various crops like grapes and strawberry (noble rot), pomegranate (bunch rot), ash mold etc. (http:// www.epicgardening.com/botrytis-cinerea). Since various types of remedial measures have been adopted in order to control the diseases but due to the genetic plasticity (Williamson *et al.*, 2007) of the *Botrytis* fungi it has been very difficult to control diseases by *Botrytis* at maximum rate. The various remedies used are:

Neem oil: The extract of the neem leaves contain terpenoides known as Azadirachtin, used against various fungi and bacteria (Gurjar *et al.*, 2012).

Copper based fungicides: Copper based nanoparticles ranges from the ~20nm diameter and ~0.3nm length were used for *Botrytis* fungi control (Ouda *et al.*, 2014).

Potassium bicarbonate based fungicides: The potassium sorbate has been used to control the post-harvest decay diseases caused by *Botrytis cinerea* (Karabulu, 2001).

Bio-char: A carbonaceous organic byproduct effective against *Botrytis* fungi (ZH Mehari *et al.*, 2015; Harel *et al.*, 2012).

Due to the genetic plasticity as given by the Williamson *et al.*, 2007, it has been seen that the various remedies have been proved very ineffective against the control of the *Botrytis cinerea*, as widespread of diseases by this fungi has been occurring upto a great extent every year worldwide. Average loss of 100 million fruit production has been damaged by this fungi every year, therefore there is a need for a change that provides a good management over this fungi. Bio-char is a new and advanced technique being used and doesn't put any residual load in the soils over time.

Various researches have been done over various plant species in order to check the results of the Bio-char towards incidence of the disease. Application of Bio-char in the tomato crop reduced incidence of *Botrytis* by 50%. It was resulted out that Bio-char could activate of responses defense genes responsible for induced resistance within the plants. The genes Pti5 (Ethylene related) and Pi2 (Jasmonic acid related) produces resistance in tomato plants against the *Botrytis cinerea* (Mehari *et al.*, 2015). Application of Bio-char at the rate of 3% w/w induces the resistance in strawberry plants against *Botrytis* and could help increasing strawberry production by 15% (De Tender *et al.*, 2016). There is an another evidence of the Bio-char in inducing the resistance against *Botrytis* fungi that application of Bio-char at the rate of 1 to 3% w/w in the soil at the time of strawberry transplanting reduces the chances of occurrence of noble rot disease. Hence it activated five genes responsible for plant defense mechanism i.e. FaPR1, Faolp2, Fraa3, Falox and FaWRKY1 (Harel *et al.*, 2012).

Bio-char against *Phytophthora* spp.

Phytophthora also credited as "water mold" hence belongs to phylum oomycota, class oomycetes and family Pythiaceae (Agrios, 2005). This genus 'Phytophthora' has been first described by Heinrich Anton de Bary in 1875 (en.wikipedia.org). The word "Phytophthora" actually means as "Plant destroyer" (Agrios, 2005). It is a very destructive kind of fungi which causes huge economic losses to growers by causing a wide variety of diseases within the various plant species. The evidences of its destructive nature has been seen and recorded as history of mycology where in 1845 it caused "Irish famine" by causing late blight of potato (*Phytophthora infestans*). This fungi hosted into a wide variety of plant species (~50) viz., potato, chili, tomato, papaya, citrus, cucurbits, peppers and other horticultural crops. Phytophthora has more than 100 species, some of them are *P. cinnamomi, P. infestans, P. sojae, P. ramorum, P. porri, P. capsici, P. citricola, P. fragariae, P.*

multivora, P. palmivora, P. nicotianae etc. They causes various types of diseases in different plant species depending upon the species of the pathogen. These include sudden death of oak tree, late blight of tomato, cucurbit blight, fruit rots, citrus canker, damping off etc.

Phytophthora is a facultative saprophyte; soil borne fungus reproduce through sexual as well as asexual means. It produces biflagellate asexual zoospores (motile spores) and sexual spores named as oospores (Agrios, 2005). They grow best at a temperature range of $10^{o}C$ to $36^{o}C$. It mostly attacks root system of the plants but in some cases fruits, leaves, stem and bark also. Under synthetic environment it rapidly grow on lima bean agar and the color of the colony is white with cottony and rosaceous to star shaped appearance (Babadoost, 2005). The sporangia appear ovoid, ellipsoid, pyriform, fusiform or obovoid depending upon the species of the pathogen. Some of the *Phytophthora* species produce asexual fruiting bodies named as chlamydospores (Babadoost, 2005), they can be present at terminal or intercalary positions on mycelium. The sexual structures of this fungi is called as antheridia and oogonia, these are heterothallic by nature (Agrios, 2005). The pathogenicity of different species of *Phytophthora* varies from each other upto great extents. The spores of this fungi can survive within the soil for several years because these are resistant to desiccation and other extreme climatic conditions. The zoospores get dispersed through the water with irrigation or rain from one place to another since they have motility or flagella for locomotion.

Since various techniques and methods have been adopted for the control of this fungi. Still there is a need for a change or an advanced method to cure the plants from this fungus. Various methods used to manage are Biological control (Weller *et al.,* 1988; Smith *et al.,* 1990); Cultural control (Shea *et al.,* 1982); Chemical control (Schwinn, 1983; Darvas, 1983); Bio-char (Shoaf *et al.,* 2016).

Bio-char as a new approach provides control of this devastating and monistic disease. It has been observed that the application of Bio-char in the soils prior transplanting or sowing crops help to reduce chances of outbreak of the diseases caused by *Phytophthora* spp. According to a research it has been found that Bio-char helps in reducing the incidence of diseases caused by *Phytophthora* spp. Researchers amended soil with Bio-char @ of 0 to 5% to check results on two woody plant species viz. *Quercusrubra* and *Acer rubrum* and concluded that Bio-char is a very useful tool in inducing resistance against stem lesions (Zwart *et al.,* 2012).

In an another research it has been found that Bio-char amendment of sweet pepper will be helpful in controlling the Phytophthora Blight (Shoaf *et al.,* 2016), it was caused by *Phytophthora capsici*; a soil borne pathogen. The spores of this fungi can thrives upto 10 years within the soil under adverse climatic conditions. Bio-char application provides a scope in controlling this fungi so as the Bio-char is of recalcitrant properties and can last for longer period of time in the soils (Lehmann *et al.,* 2007).

Bio-char against *Rhizoctonia* spp.

The dictionary meaning of Rhizoctonia is "root killer". The fungi *Rhizoctonia* has been characterized under the division Basidiomycota, class Agaricomycetes and family Ceratobasidiaceae (Agrios, 2005). The sexual stage of this fungi is *Thanatephorus*. This fungi do not produces the spores but they are composed of the hyphae and sclerotia.

Table.1 Effects of different feed stocks on different pathogen at different concentrations.

Pathogen	Host plant	Feedstocks	Reference	Biochar % needs attention
Botrytis cinerea	*Lycopersicum esculatum*	Citrus wood (3, 5%) Eucalyptus wood (0.5, 1, 3%) Olive pomice (0.5, 1, 3%) Greenhouse waste (0.5, 1, 3%)	Elad *et al.* (2010) Elad *et al.* (2011) Mehari*et al.* (2015)	N 3% N
Botrytis cinerea	*Capsicum annum*	Greenhouse waste (0.5, 1, 3%)	Elad *et al.* (2010)	N
Botrytis cinerea	*Fragia x ananassa*	Citrus wood, Greenhouse waste (3, 5%) Holm oak (1, 3%)	MellerHarel*et al.* (2012) De Tender *et al.* (2016)	N N
Fusarium oxysporum f.sp asparagi	*Asparagus sp.*	Commercial Quest biochar (0.5, 1.5, 3%) Coconut charcoal (10, 30%)	Elmer and Pignatello (2011) Matsubara *et al.* (2002)	N N
Fusarium oxysporum f.sp *lycopersici*	*L. esculatum*	Wood & Green waste biochar (3% v/v)	Akhter *et al.* (2015) Akhter *et al.* (2016)	3% (v/v)3
Phytophthoracactorum	*Acer rubrum*	Wood (0.5, 10, 20%)	Zwart and Kim (2012)	>5%
Phytophthora Cinnanomi	*Quercusrubra*	Wood (0.5, 10, 20%)	Zwart and Kim (2012)	>5%
Rhizoctonia solani	*Glycine max, Pisumsativum, Beta vulgaris, Medicagosativa, C. annum, L. esculatum, C. sativus, Raphanussativus, D. carota, Allium Ampeloprasum*	Maple bark (1, 3, 5%)	Copley *et al.* (2015)	3%
	Cucumissativus *Phaseolus vulgaris*	Greenhouse waste and Eucalyptus wood (0.5, 1, 3%)	Jaiswal*et al.* (2014) Jaiswal*et al.* (2015)	1% 3%

Courtesy: Frenkel*et al*., 2017

The sclerotium, is a formation of cells named monilioid cells that fuse together to form thishard structure. Spores are absent in this fungi and branching of the hyphae has been found at right angle (Agrios, 2005). Various species does exist and are typically saprophytic but few of them are facultative in nature. These species has been divided into two groups one is binucleate and another is multinucleate species.

The only binucleate species is *R. cerealis* and the other species are multinucleate viz. *R. bataticola*, *R. carotae*, *R. fragariae*, *R. leguminicols*, *R.* solani, *R. oryzae*, *R. rubi* and *R. zeae*. Every species have different host range and causes various types of diseases in their hosts. They get reproduce through a special mechanism named as anastomosis; the fusion of the hyphae (Hietala *et al.,* 1994).

The pathogenicity of every species varies from each other depending upon the genetic nature of the pathogen. Out of these species the *Rhizoctonia solani* causes great loss to various crop species worldwide annually. It causes sheath blight in rice, black scurf in potato, damping off in seedlings and belly rot in cucumber. These were mostly necrotrophic by nature which means they kill their host before colonizing the whole plants. The symptoms of various species differ simultaneously depending upon the host range and other climatic conditions. Like brown patches at 18 to 25^{o}C soil temperature, large patches at 10 to 21^{o}C soil temperature in turf disease.

The various controls measures have been used including cultural and chemical treatments but chemical measures have been widely adopted by the farmers in order to get the immediate results. The various treatments used against *Rhizoctonia*are Carboximides (Kataria *et al.,* 1996); Benzimidazoles (Taneja *et al.,* 1982); Carbamates (Ernst *et al.,* 1965); DMI fungicides (Tsuda *et al.,* 2004); Bio-char (Jaiswal *et al.,* 2015).

It has been seen in various researches that the application of Bio-char in the soils reduced the incidence of the various soil borne diseases (Lehmann *et al.,* 2007). Application of Bio-char in the soils bean crops are grown had shown a great response to the plant growth and resistance against *Rhizoctonia* species (Jaiswal *et al.,* 2014). The concentration used for application ranges from less than 1% because they have seen that the application of Bio-char at 3% increases the severity of the *Rhizoctonia* species (Jaiswal *et al.,* 2015). According to an another research performed by the Jaiswal *et al.,* 2015, it has seen that the Bio-char also have the hormesis effect which means the lower dose is beneficial for disease suppression but high dose increases disease incidence. It has seen that the Bio-char prepared from eucalyptus and green house wastes reduces the occurrence of *Rhizoctonia* fungi. The application of 1% eucalyptus and 0.5% green house waste Bio-char help in the suppression of *Rhizoctonia* disease (Jaiswal *et al.,* 2014). There is another example where the application of Bio-char has increases the incidence of this disease. In a research it has been seen that the Bio-char prepared from the maple tree increases the incidence of the damping off severity in various plant species grown under soil less media (Tanya *et al.,* 2015).

As we discussed that Biochar plays a significant role in suppressing the various plant diseases when used under field conditions for various concentrations. Different crops reacts differently for different concentrations of Biochar. As in various researches it has seen that the concentrations at 3% proved to be very effective for suppressing a number of diseases. List of the studies that tested Biochar in growth media on soil borne and foliar plant diseases. The last column gives the Biochar concentration which exhibits negative influence on plant health compared with the control (no Biochar) or compared with the Biochar concentration having the most positive effect on disease suppression treatment.

References

Agrios, G. N. (2005). Plant Pathology. 5th eds. *Department of Plant Pathology. University of Florida. United States of America*.

Akhter, A., Hage-Ahmed, K., Soja, G., and Steinkellner, S. (2015). Compost and biochar alter mycorrhization, tomato root exudation, and development of *Fusarium oxysporum* f. sp. lycopersici. *Frontiers in plant science*, *6*, 529.

Babadoost, M. (2004). Phytophthora blight: a serious threat to cucurbit industries. *Urbana*, *51*, 61801.

Blandino, M., Minelli, L., & Reyneri, A. (2006). Strategies for the chemical control of Fusarium head blight: effect on yield, alveographic parameters and deoxynivalenol contamination in winter wheat grain. *European Journal of Agronomy*, *25*(3), 193-201.

Boddy, L. (2015). Pathogens of Autotrophs. In *The Fungi (Third Edition)* (pp. 245-292). Copley, T. R., Aliferis, K. A., & Jabaji, S. (2015). Maple bark biochar affects Rhizoctoniasolani metabolism and increases damping-off severity. *Phytopathology*, *105*(10), 1334-1346

Carisse, O., Tremblay, D. M., McDonald, M. R., Brodeur, L., and McRoberts, N. (2011). Management of Botrytis leaf blight of onion: the Québec experience of 20 years of continual improvement. *Plant disease*, *95*(5), 504-514.

Copley, T. R., Aliferis, K. A., and Jabaji, S. (2015). Maple bark biochar affects Rhizoctonia solani metabolism and increases damping-off severity. Phytopathology, 105(10), 1334-1346.

Darvas, J. M. (1983). Five years of continued chemical control of phytophthora root rot of avocados. South African Avocado Growers' Association Yearbook, 6, 72-73.

Datnoff, L. E., Nemec, S., and Pernezny, K. (1995). Biological control of *Fusarium crown* and root rot of tomato in Florida using *Trichoderma harzianum* and Glomusintraradices. *Biological Control*, *5*(3), 427-431.

De Nijs, M., Rombouts, F., and Notermans, S. (1996). Fusarium molds and their mycotoxins. *Journal of Food Safety*, *16*(1), 15-58.

De Tender, C., Haegeman, A., Vandecasteele, B., Clement, L., Cremelie, P., Dawyndt, P.,...& Debode, J. (2016). Dynamics in the strawberry rhizosphere microbiome in response to biochar and Botrytis cinerea leaf infection. *Frontiers in microbiology*, *7*, 2062.

Dorais, M., Martinez, C., Diop, M., Theriault, M., Menard, C., & Pepin, S. (2015, June). Assessing the potential of biochar as a growing media component for potted plants. In *International Symposium on Innovation in Integrated and Organic Horticulture (INNOHORT) 1137* (pp. 19-26).

Elmer, P. A., and Michailides, T. J. (2007). Epidemiology of *Botrytis cinerea* in orchard and vine crops. In *Botrytis: Biology, pathology and control* (pp. 243-272). Springer, Dordrecht.

Elmer, W. H., and Pignatello, J. J. (2011). Effect of biochar amendments on mycorrhizal associations and *Fusarium crown* and root rot of asparagus in replant soils. *Plant Disease*, *95*(8), 960-966.

Ernst, B., Rudolf, H., and Paul-Ernst, F.

(1965). U.S. Patent No. 3,215,595. Washington, DC: U.S. Patent and Trademark Office.

Gurjar, M. S., Ali, S., Akhtar, M., and Singh, K. S. (2012). Efficacy of plant extracts in plant disease management. *Agricultural Sciences*, *3*(3), 425.

Harel, Y. M., Elad, Y., Rav-David, D., Borenstein, M., Shulchani, R., Lew, B., and Graber, E. R. (2012). Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant and Soil*, *357*(1-2), 245-257.

Hietala, A. M., Sen, R., and Lilja, A. (1994). Anamorphic and teleomorphic characteristics of a uninucleate Rhizoctonia sp. isolated from the roots of nursery grown conifer seedlings. Mycological Research, 98(9), 1044-1050.

https://www.apsnet.org/edcenter/intropp/lessons/fungi/Basidiomycetes/Pages/Rhizoctonia.aspx

https://www.apsnet.org/edcenter/intropp/lessons/fungi/Oomycetes/Pages/Phytophthora.asp

Jaiswal, A. K., Elad, Y., Graber, E. R., and Frenkel, O. (2014). *Rhizoctonia solani* suppression and plant growth promotion in cucumber as affected by biochar pyrolysis temperature, feedstock and concentration. *Soil Biology and Biochemistry*, *69*, 110-118.

Jaiswal, A. K., Frenkel, O., Elad, Y., Lew, B., and Graber, E. R. (2015). Non-monotonic influence of biochar dose on bean seedling growth and susceptibility to *Rhizoctonia solani*: the “Shifted R max-Effect”. *Plant and soil*, *395*(1-2), 125-140.

Karabulut, O. A., Lurie, S., and Droby, S. (2001). Evaluation of the use of sodium bicarbonate, potassium sorbate and yeast antagonists for decreasing postharvest decay of sweet cherries. *Postharvest Biology and Technology*, *23*(3), 233-236.

Kataria, H. R., and Gisi, U. (1996). Chemical control of Rhizoctonia species. In Rhizoctonia species: taxonomy, molecular biology, ecology, pathology and disease control (pp. 537-547). Springer, Dordrecht.

Lehmann, J. (2007). Bio-energy in the black. *Frontiers in Ecology and the Environment*, *5*(7), 381-387.

Lehmann, J., Kuzyakov, Y., Pan, G., and Ok, Y. S. (2015). Biochars and the plant-soil interface.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota–a review. *Soil biology and biochemistry*, *43*(9), 1812-1836.

Linnemannstöns, P., Schulte, J., del Mar Prado, M., Proctor, R. H., Avalos, J., and Tudzynski, B. (2002). The polyketide synthase gene pks4 from Gibberella fujikuroi encodes a key enzyme in the biosynthesis of the red pigment bikaverin. *Fungal Genetics and Biology*, *37*(2), 134-148.

Mehari, Z. H., Elad, Y., Rav-David, D., Graber, E. R., and Harel, Y. M. (2015). Induced systemic resistance in tomato (*Solanum lycopersicum*) against Botrytis cinerea by biochar amendment involves jasmonic acid signaling. *Plant and soil*, *395*(1-2), 31-44.

Méndez, A., Gómez, A., Paz-Ferreiro, J., and Gascó, G. (2012). Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. *Chemosphere*, *89*(11), 1354-1359.

Mitchell, P. J., Dalley, T. S., & Helleur, R. J. (2013). Preliminary laboratory production and characterization of biochars from lignocellulosic municipal waste. *Journal of Analytical and Applied Pyrolysis*, *99*, 71-78.

Oerke, E. C. (2006). Crop losses to pests. *The*

Journal of Agricultural Science, *144*(1), 31-43.

Ouda, S. M. (2014). Antifungal activity of silver and copper nanoparticles on two plant pathogens, *Alternaria alternata* and *Botrytis cinerea*. *Research Journal of Microbiology*, *9*(1), 34-42.

Pineda-Valdes, G., Ryu, D., Hanna, M. A., and Bullerman, L. B. (2003). Reduction of moniliformin in corn by heat processing. *Journal of food science*, *68*(3), 1031-1035.

Pirgozliev, S. R., Edwards, S. G., Hare, M. C., and Jenkinson, P. (2003). Strategies for the control of Fusarium head blight in cereals. *European Journal of Plant Pathology*, *109*(7), 731-742.

Proctor, R. H., Desjardins, A. E., Plattner, R. D., and Hohn, T. M. (1999). A polyketide synthase gene required for biosynthesis of fumonisinmycotoxins in Gibberellafujikuroi mating population A. *Fungal Genetics and Biology*, *27*(1), 100-112.

Raaijmakers, J. M., Leeman, M., Van Oorschot, M. M., Van der Sluis, I., Schippers, B., and Bakker, P. A. H. M. (1995). Dose-response relationships in biological control of *Fusarium wilt* of radish by Pseudomonas spp. *Phytopathology*, *85*(10), 1075-1080.

Raaijmakers, J. M., Leeman, M., Van Oorschot, M. M., Van der Sluis, I., Schippers, B., and Bakker, P. A. H. M. (1995). Dose-response relationships in biological control of *Fusarium wilt* of radish by Pseudomonas spp. *Phytopathology*, *85*(10), 1075-1080.

Romanazzi, G., and Feliziani, E. (2014). *Botrytis cinerea* (Gray Mold). In *Postharvest decay* (pp. 131-146).

Savary, S., Ficke, A., Aubertot, J. N., and Hollier, C. (2012). Crop losses due to diseases and their implications for global food production losses and food security.

Scheel, C. M., Hurst, S. F., Barreiros, G., Akiti, T., Nucci, M., and Balajee, S. A. (2013). Molecular analyses of *Fusarium* isolates recovered from a cluster of invasive mold infections in a Brazilian hospital. *BMC infectious diseases*, *13*(1), 49.

Schwinn, F. J. (1983). New developments in chemical control of Phytophthora. *Phytophthora. Its Biology, Taxonomy. Ecology and Pathology. The American Phytopathology Society, St. Paul Minnesota*, 327-334.

Shea, S., and Broadbent, P. (1982). Developments in cultural and biological control of Phytophthora diseases. The Authors.

Shoaf, N., Hoagland, L., and Egel, D. S. (2016). Suppression of phytophthora blight in sweet pepper depends on biochar amendment and soil type. *HortScience*, *51*(5), 518-524.

Singh, D. K. (2007). Insecticidal methods of pest control.

Sivan, A., and Chet, I. (1986). Biological control of Fusarium spp. in cotton, wheat and muskmelon by *Trichoderma harzianum*. *Journal of Phytopathology*, *116*(1), 39-47.

Smil, V. (2000). Energy in the twentieth century: resources, conversions, costs, uses, and consequences. *Annual Review of Energy and the Environment*, *25*(1), 21-51.

Smith, V. L., Wilcox, W. F., & Harman, G. E. (1990). Potential for biological control of Phytophthora root and crown rots of apple by Trichoderma and Gliocladium spp. *Phytopathology*, *80*(9), 880-885.

Snyder, W. C., and Hansen, H. N. (1940). The species concept in Fusarium. *American Journal of Botany*, *27*(2), 64-67. Samuels, G. J., Nirenberg, H. I., & Seifert, K. A. (2001). Perithecial species of Fusarium. In *Fusarium. Paul*

E. Nelson memorial symposium (pp. 1-15). American Phytopathological Society, St. Paul, MN.

Song, W., Zhou, L., Yang, C., Cao, X., Zhang, L., & Liu, X. (2004). Tomato *Fusarium wilt* and its chemical control strategies in a hydroponic system. *Crop protection*, *23*(3), 243-247.

Spokas, K. A., Koskinen, W. C., Baker, J. M., & Reicosky, D. C. (2009). Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere*, *77*(4), 574-581.

Strange, R. N., & Scott, P. R. (2005). Plant disease: a threat to global food security. *Annual review of phytopathology*, *43*.

Taneja, M., & Grover, R. K. (1982). Efficacy of benzimidazole and related fungicides against Rhizoctonia solani and R. bataticola. Annals of Applied Biology, 100(3), 425-432.

Teng, P. S., & Krupa, S. V. (1980). Crop loss assessment.

Tsuda, M., Itoh, H., & Kato, S. (2004). Evaluation of the systemic activity of simeconazole in comparison with that of other DMI fungicides. Pest management science, 60(9), 875-880.

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil use and management*, *27*(2), 205-212.

Van Peer, R., Niemann, G. J., & Schippers, B. (1991). Induced resistance and phytoalexin accumulation in biological control of *Fusarium wilt* of carnation by Pseudomonas sp. strain WCS 417 r. *Phytopathology*, *81*(7), 728-734.

Vassilev, N., Martos, E., Mendes, G., Martos, V., & Vassileva, M. (2013). Biochar of animal origin: a sustainable solution to the global problem of high-grade rock phosphate scarcity?. *Journal of the Science of Food and Agriculture*, *93*(8), 1799-1804.

Warnock, D. D., Lehmann, J., Kuyper, T. W., and Rillig, M. C. (2007). Mycorrhizal responses to Bio-char in soil–concepts and mechanisms. *Plant and soil*, *300*(1-2), 9-20.

Weller, D. M. (1988). Biological control of soilborne plant pathogens in the rhizosphere with bacteria. *Annual review of phytopathology*, *26*(1), 379-407.

Williamson, B., Tudzynski, B., Tudzynski, P., and van Kan, J. A. (2007). Botrytis cinerea: the cause of grey mould disease. *Molecular plant pathology*, *8*(5), 561-580.

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www.epicgardening.com/botrytis-cinerea

Xu, R. K., Xiao, S. C., Yuan, J. H., & Zhao, A. Z. (2011). Adsorption of methyl violet from aqueous solutions by the biochars derived from crop residues. *Bioresource technology*, *102*(22), 10293-10298.

Zadoks, T. C. (1967). Epidemiology of wheat rust in Europe. International Journal of Pest Management B, 13(1), 29-46.

Zwart, D. C., and Kim, S. H. (2012). Biochar amendment increases resistance to stem lesions caused by Phytophthora spp. in tree seedlings. *HortScience*, *47*(12), 1736-1740.