

Biochar and *Trichoderma* spp. in management of plant diseases caused by soilborne fungal pathogens: a review and perspective

Biochar e *Trichoderma* spp. no manejo de doenças de plantas causadas por patógenos fúngicos do solo: uma revisão e perspectiva

Biochar y *Trichoderma* spp. en el manejo de enfermedades de las plantas causadas por hongos patógenos transmitidos por el suelo: una revisión y perspectiva

Received: 10/28/2021 | Reviewed: 11/06/2021 | Accept: 11/17/2021 | Published: 11/27/2021

Erika Valente de Medeiros

ORCID: <https://orcid.org/0000-0001-5543-9414>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: erika.valente@ufape.edu.br

Lucas Figueira da Silva

ORCID: <https://orcid.org/0000-0002-6537-9125>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: lucas_f.silva@hotmail.com

Jenifer Sthephanie Araújo da Silva

ORCID: <https://orcid.org/0000-0002-5064-669X>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: jenifersthephanie12@hotmail.com

Diogo Paes da Costa

ORCID: <https://orcid.org/0000-0002-8551-7345>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: diogocosta1@yahoo.com.br

Carlos Alberto Fragoso de Souza

ORCID: <https://orcid.org/0000-0002-8388-4897>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: carlos_fragoso1@hotmail.com

Lúcia Raquel Ramos Berger

ORCID: <https://orcid.org/0000-0002-5039-8198>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: luciaraqueldramosberger@gmail.com

José Romualdo de Souza Lima

ORCID: <https://orcid.org/0000-0001-9535-9208>
Universidade Federal do Agreste de Pernambuco, Brazil
E-mail: romualdo.lima@ufape.edu.br

Claude Hammecker

ORCID: <https://orcid.org/0000-0001-5594-4891>
Soil-Agrosystem-Hydrosystem interaction lab-LISAH, France
E-mail: claud.hammecker@ird.fr

Abstract

A better understanding of the use of biochar with *Trichoderma* spp. (TRI), considered the most studied tool for biological control, would increase our ability to set priorities. However, no studies exist using the two inputs on plant disease management. Here, we hypothesized that biochar and TRI would be used for the management of soilborne plant pathogens, mainly due to changes in soil properties and its interactions. To test this hypothesis, this review assesses papers that used biochar and TRI against plant diseases and we summarize the handling mechanisms for each input. Biochar acts by mechanisms: induction to plant resistance, sorption of allelopathic and fungitoxic compounds, increase of beneficial microorganisms, changes the soil properties that promote health and nutrient availability. *Trichoderma* as biocontrol agents by different mechanisms: mycoparasitism, enzyme and secondary metabolic production, plant promoter agent, natural decomposition agent, and biological agent of bioremediation. Overall, our findings expand our knowledge about the reuse of wastes transformed in biochar combined with *Trichoderma* has potential perspective to formulate products as alternative management tool of plant disease caused by soilborne fungal pathogen and add important information that can be suitable for development of strategy for use in the global health concept.

Keywords: Black carbon; Biocontrol; Soil Health; Management practices; Plant growth-promoting.

Resumo

Uma melhor compreensão do uso do biochar com *Trichoderma* spp. (TRI), considerada a ferramenta mais estudada para o controle biológico, aumentaria nossa capacidade de estabelecer prioridades. No entanto, não existem estudos utilizando os dois insumos no manejo de doenças de plantas. Aqui, hipotetizamos que o biochar e o TRI seriam usados para o manejo de patógenos vegetais transmitidos pelo solo, principalmente devido às mudanças nas propriedades do solo e suas interações. Para testar essa hipótese, esta revisão avalia artigos que usaram biochar e TRI contra doenças de plantas e resumimos os mecanismos de manuseio para cada entrada. Biochar atua por mecanismos: indução à resistência das plantas, sorção de compostos alelopáticos e fungitóxicos, aumento de microrganismos benéficos, altera as propriedades do solo que promovem a saúde e a disponibilidade de nutrientes. *Trichoderma* como agente de biocontrole por diferentes mecanismos: micoparasitismo, produção enzimática e metabólica secundária, agente promotor de plantas, agente de decomposição natural e agente biológico de biorremediação. No geral, nossos resultados expandem nosso conhecimento sobre o reaproveitamento de resíduos transformados em biochar combinado com *Trichoderma*, perspectiva potencial para formular produtos como ferramenta alternativa de manejo de doenças de plantas causadas por patógenos fúngicos de solo e adicionar informações importantes que podem ser adequadas para o desenvolvimento de estratégia para uso em o conceito de saúde global.

Palavras-chave: Carbono negro; Biocontrole; Saúde do solo; Práticas de manejo; Promoção de crescimento de plantas.

Resumen

Una mejor comprensión del uso de biocarbón con *Trichoderma* spp. (TRI), considerada la herramienta más estudiada para el control biológico, aumentaría nuestra capacidad para establecer prioridades. Sin embargo, no existen estudios que utilicen los dos insumos sobre el manejo de enfermedades de las plantas. Aquí, planteamos la hipótesis de que el biocarbón y el TRI se utilizarían para el manejo de patógenos de plantas transmitidos por el suelo, principalmente debido a cambios en las propiedades del suelo y sus interacciones. Para probar esta hipótesis, esta revisión evalúa artículos que utilizaron biochar y TRI contra enfermedades de las plantas y resumimos los mecanismos de manejo para cada entrada. El biocarbón actúa por mecanismos: inducción a la resistencia de las plantas, sorción de compuestos alelopáticos y fungitóxicos, aumento de microorganismos benéficos, cambiá-las propiedades del suelo que promueven la salud y la disponibilidad de nutrientes. *Trichoderma* como agentes de biocontrol por diferentes mecanismos: micoparasitismo, producción enzimática y metabólica secundaria, agente promotor vegetal, agente de descomposición natural y agente biológico de biorremediación. En general, nuestros hallazgos amplían nuestro conocimiento sobre la reutilización de desechos transformados en biocarbón combinado con *Trichoderma* tiene una perspectiva potencial para formular productos como una herramienta de manejo alternativa de enfermedades de las plantas causadas por patógenos fúngicos transmitidos por el suelo y agregar información importante que puede ser adecuada para el desarrollo de una estrategia de uso en el concepto de salud global.

Palabras clave: Carbono negro; Biocontrol; Salud del suelo; Prácticas de manejo; Promoción del crecimiento vegetal.

1. Introduction

The growing need for a sustainable food production represents a major challenge for crop producers. The increase in demand for healthier food and the exponential growth of the world population pose difficulties to food production, intensified by climatic adversities as well as constant attacks of pests and diseases that compromise crop production. Plant diseases caused by soilborne pathogens decrease crop yields, resulting in great socioeconomic damage, due to the difficulty to diagnose and control these diseases, especially when symptoms occur only in the roots and not observed in the shoots (Ghorbanpour et al., 2018). Soil pathogens comprise fungi, oomycetes, bacteria, viruses, and nematodes (Montiel-Rozas et al., 2019). Fungi stand out as the largest group causing root diseases in cropped plant species, since they occur in all agricultural ecosystems. Although diverse, soil pathogens share similarities, such as the influence by biotic and abiotic soil components, poor dispersion (Liu et al., 2020), as well as the capacity of developing structures of resistance that allow these microorganisms to survive long periods in the soil without a host plant, hindering their management.

Thus, research on efficient and sustainable management strategies is essential for a more integrative agriculture. The use of synthetic chemicals is the main method of pest and disease control in agriculture. However, the indiscriminate use of synthetic products has increased the resistance of pest and pathogens, damaged the environment, and affected human health (Montiel-Rozas et al., 2019). Alternative techniques for disease control, such as biological control (Zin & Badaluddin, 2020) has grown substantially in recent years with use of *Bacillus* spp., *Metarhizium* spp., and *Trichoderma* spp. Fungi of the genus

Trichoderma are agents of importance in agriculture for biological control, due to their high potential as antagonist against many phytopathogens. The capacity of *Trichoderma* to remain in the soil for long periods characterizes an advantage for a preventive biological control (Da Silva et al., 2016). In addition, this fungus promotes the growth of host plants and stimulates plant resistance to the attack by pathogenic microorganisms that penetrate and colonize the root surface, limiting plant growth (Montiel-Rozas et al., 2019).

In recent years, biochar has been considered an important issue in management of soilborne phytopatogens since they provide several benefits for sustainable food production (Medeiros et al., 2021). Biochar is a solid compound that results from organic matter decomposition under high temperatures under low oxygen concentrations in a pyrolysis process (Lehmann et al., 2011). Silva et al. (2021) has studied the use of biochar as a low-cost alternative for waste reuse in agriculture, benefiting the soil, microorganisms, culture, and the environment. Biochar improves the soil physical, chemical, and biological parameters. It also increases retention of water and nutrients, favoring carbon sequestration and benefiting the soil microbiota (Lima et al., 2018; Medeiros et al., 2020a). Biochar has been used for the management of plant diseases caused by pathogens in the soil (Medeiros et al., 2021).

However, studies on the use of biochar combined with *Trichoderma* are still incipient. Therefore, it is crucial to investigate their use in combination to provide farmers a tool for the management of plant diseases caused by soilborne pathogens. Here, we hypothesized that the co-application of biochar and TRI would be used to the management of soilborne plant pathogen, mainly due changes soil properties and its interactions. To test this hypothesis, this review assesses twenty papers with biochar and thirty-three with TRI used as alternative tool to managemen plant diseases caused by soilborne pathogen and we summarize the handling mechanisms for each input.

2. Methodology

This study is a narrative review about the use of Biochar and *Trichoderma* spp. in the management of plant diseases caused by soil fungal pathogens. The selected literatures were extracted from the platforms: SciELO, ScienceDirect, Elsevier, PubMed, SpringerLink and Jornal CAPES.

3. Development

3.1 Strategies for managing diseases caused by soilborne pathogens

Different strategies have been used to manage plant diseases caused by soil pathogens, such as the use of resistant cultivars, crop rotation, addition of organic matter sources, physical, chemical, and biological control techniques (Kazerooni et al., 2020; Medeiros et al., 2021). The use of resistant cultivars is a management strategy used in cropped areas with a history of pathogen infestation in the soil. This technique must be handled with care, as pathogens have a great capacity to overcome plant resistance, making them more susceptible to the disease. Crop rotation consists of alternating cultivation of different plant species to avoid as much as possible the contact of pathogens with susceptible crops (Hong et al., 2020). The introduction of new crops through this method allows the entry of microorganisms antagonistic against several soil phytopathogens (Larkin & Brewer, 2020).

On the other hand, the use of chemical control has increased considerably due to the expansion of agricultural areas over the years. This method involves the use of chemical compounds with specific action mechanisms that eradicate target microorganisms (Montiel-Rozas et al., 2019). However, it is a practice that must be adopted carefully due to toxicological effects and occurrence of resistant phytopathogens (Coelho et al., 2020).

The biological control uses microorganisms that reduce the attack of pathogenic organisms through various

interactions, such as antagonism, in which an organism produces substances that inhibit the development of others (Silva et al., 2017). Several microorganisms have been studied regarding mechanisms for their potential use as biocontrol agents. Fungi of the genus *Trichoderma* have mechanisms, such as antibiosis, predation, competition, and even induction of resistance to plants (Zin & Badaluddin, 2020). Therefore, the use of these fungi reduces the use of chemicals in agriculture, mitigating damages to the environment and providing more sustainable production.

3.2 Use of *Trichoderma* spp. in the biological control of plant diseases

The genus *Trichoderma* is widely studied and has several applications in the industry, in the environment, and mainly in agriculture. *Trichoderma* is known for the diverse benefits to plants, promoting plant growth (Medeiros et al., 2020a), producing phytohormones and enzymes that increase the root absorption area (Lee et al., 2016). These fungi promote phosphate solubilization (Chagas et al., 2017) and insoluble micronutrient, improving absorption of water and nutrients and inducing resistance to plants, contributing to the production of more vigorous plants. *Trichoderma* is a natural decomposition agent and thus used as a biological agent of bioremediation.

Moreover, it is the most studied species for biocontrol of plant disease (Zin & Badaluddin, 2020), for diverse soilborne pathogens (Elshahawy & El-Mohamedy, 2019; Lu et al., 2020). Different pathosystems using *Trichoderma* spp. in the biocontrol of plant diseases are shown in Table 1. For example, isolates of *Trichoderma harzianum* inhibited the growth of pathogen *Macrophomina phaseolina* (Tassi) Goind, a causal agent of coal rot in soybean plants, increasing the length of stem and roots of plants in the field (Khalili et al., 2016). Sallam et al. (2019) evaluated the antagonistic function of isolates of *Trichoderma* spp. and observed that all isolates inhibited the action of the pathogen *Fusarium oxysporum* f.sp. *lycopersici*, the causal agent of tomato wilt. The most commercialized and used strains worldwide are *T. harzianum* (Table 1), followed by *T. atroviride*, *T. asperellum*, *T. lignorum*, *T. catenulatum*, *T. koningiopsis*, *T. virens*, *T. fertile*, and *T. stromaticum* (Bettiol et al., 2019).

3.3 Plant disease control mechanisms by *Trichoderma* spp.

The antagonism of *Trichoderma* involves a variety of mechanisms that confer success to the biocontrol of phytopathogens. *Trichoderma* is capable of surviving in unfavorable conditions and it also has a high reproductive capacity, efficient use of nutrients, modification of rhizosphere, root colonization, induction of resistance to host plants, and great aggressiveness towards phytopathogens (Kumar et al., 2017). *Trichoderma* also shows competition with other microorganisms for space and nutrients, inducing systemic resistance of plants to pathogens (Wang et al., 2020).

Mycoparasitism relationships are mechanisms for the biocontrol of pathogens that the *Trichoderma* species most use. Antagonistic fungi recognize and attack pathogens directly, limiting their growth by strangling their hyphae, cause pathogen death (Alfiky, 2019), and excretes secondary metabolites and enzymes, such as exoglucanases, chitinases, and proteases that degrade the cell wall of phytopathogenic fungi (Da Silva et al., 2016).

Trichoderma harzianum releases peptaibols, a family of antimicrobial peptides produced as secondary metabolism (Nawrocka & Małolepsza, 2013). These peptaibols inhibit the glucan synthase activity in pathogenic fungi β -(1, 3), an enzyme that synthesizes β -(1, 3) glucan and reduces the blocks by synthesizing cell wall polysaccharides due to the incorporation of uridine diphosphate (UDP) and glucose (UDP-Glc) (Zin & Badaluddin, 2020).

Briefly, the mechanisms used by *Trichoderma* to control plant diseases caused by soilborne pathogens are: (i) mycoparasitism, (ii) enzyme and secondary methabolic production, (iii) plant promoter agent, (iv) natural decomposition agent, and (v) biological agent of bioremediation.

Tabela 1. Studies that used *Trichoderma* spp. as a strategy to manage plant diseases caused by soilborne pathogen.

<i>Trichoderma</i> species	Crop	Phytopathogen	Reference
<i>Trichoderma parareesei</i> , <i>T. harzianum</i> , <i>T. koningii</i>	Banana	<i>Fusarium oxysporum</i> f. <i>ubense</i>	Al-ani & Albaayit, (2018)
<i>T. harzianum</i> , <i>T. koningii</i> , <i>T. pseudokoningii</i> , <i>T. viride</i> , <i>T. virens</i> , <i>T. atroviride</i> , and <i>T. reesei</i>	Brinjal	<i>Fusarium oxysporum</i> f. <i>melongenae</i>	Cherkupally et al., (2017)
<i>T. asperellum</i> , <i>T. harzianum</i> , <i>T. citrinoviride</i> , and <i>T. erinaceum</i>	Carnation	<i>Sclerotinia sclerotiorum</i>	Vinodkumar et al., (2017)
<i>T. aureoviride</i> , <i>T. harzianum</i>	Cassava	<i>Fusarium solani</i> , <i>Scybalidium lignicola</i>	Da Silva et al., (2016); Silva et al., (2017)
<i>T. asperellum</i> , <i>T. viride</i> , <i>T. harzianum</i> , <i>T. reesei</i> , <i>T. virens</i>	Chilli	<i>Fusarium oxysporum</i> , <i>Phytophthora capsici</i> , <i>Rhizoctonia solani</i>	Jiang et al., (2016); Vinodkumar et al., (2017)
<i>T. virens</i> , <i>T. koningii</i> , <i>T. viride</i> , <i>T. harzianum</i>	Groundnut	<i>Athelia rolfsii</i> (as <i>Sclerotium rolfsii</i>)	Hirpara et al., (2016); Hirpara et al., (2017)
<i>T. asperellum</i> , <i>T. harzianum</i> , <i>T. gamsii</i>	Maize	<i>Fusarium graminearum</i> , <i>Fusarium verticillioides</i>	Li et al., (2016); Saravanakumar et al., (2017); He et al., (2019); Galletti et al., (2020); Lu et al., (2020)
<i>T. harzianum</i>	Onion	<i>Stromatinia cepivora</i> , <i>Sclerotium rolfsii</i> (as <i>Sclerotium rolfsii</i>)	Zúñiga-Mendoza & Ceja-Torres (2017)
<i>T. harzianum</i>	Pea	<i>Fusarium oxysporum</i> f. <i>pisi</i>	Checa et al., (2017)
<i>T. atroviride</i> , <i>T. harzianum</i>	Rice	<i>Rhizoctonia solani</i> , <i>Sarocladium oryzae</i>	Bora, (2019); Chaudhary et al., (2020)
<i>T. asperelloides</i> , <i>T. koningiopsis</i> , <i>T. atroviride</i> , <i>T. virens</i> , <i>T. harzianum</i>	Soybean.	<i>Fusarium virguliforme</i> , <i>Macrophomina phaseolina</i> , <i>Sclerotinia sclerotiorum</i>	Khaled & Taheri, (2016); Zhang et al., (2016); Haddad et al., (2017); Sumida et al., (2018); Pimentel et al., (2020)
<i>T. harzianum</i>	Sugarcane	<i>Colletotrichum falcatum</i>	Elamathi et al., (2018)
<i>T. asperellum</i> , <i>T. harzianum</i> , <i>T. viride</i>	Tomato	<i>Botrytis cinérea</i> , <i>Fusarium oxysporum</i> f. <i>lycopersici</i>	Moosa eta al., (2017); Kuzmanovska et al., (2018)
<i>Trichoderma</i> sp., <i>T. harzianum</i> , <i>T. koningii</i>	Wheat	<i>Bipolaris sorokiniana</i> , <i>Fusarium sudanense</i> , <i>F. culmorum</i> , <i>F. graminearum</i> and <i>F. verticillioides</i> , <i>Zymoseptoria tritici</i> , <i>Cochliobolus sativus</i> , <i>Alternaria alternata</i>	Dendouga et al., (2016); Stocco et al., (2016); El-Gremi et al., (2017); Bhandari et al., (2017); Larran et al., (2020)
<i>T. harzianum</i>	Yam	<i>Fusarium oxysporum</i>	Nwankiti & Gwa, (2018)

Source: Authors.

3.4 Use of biochar as management tool of plant diseases

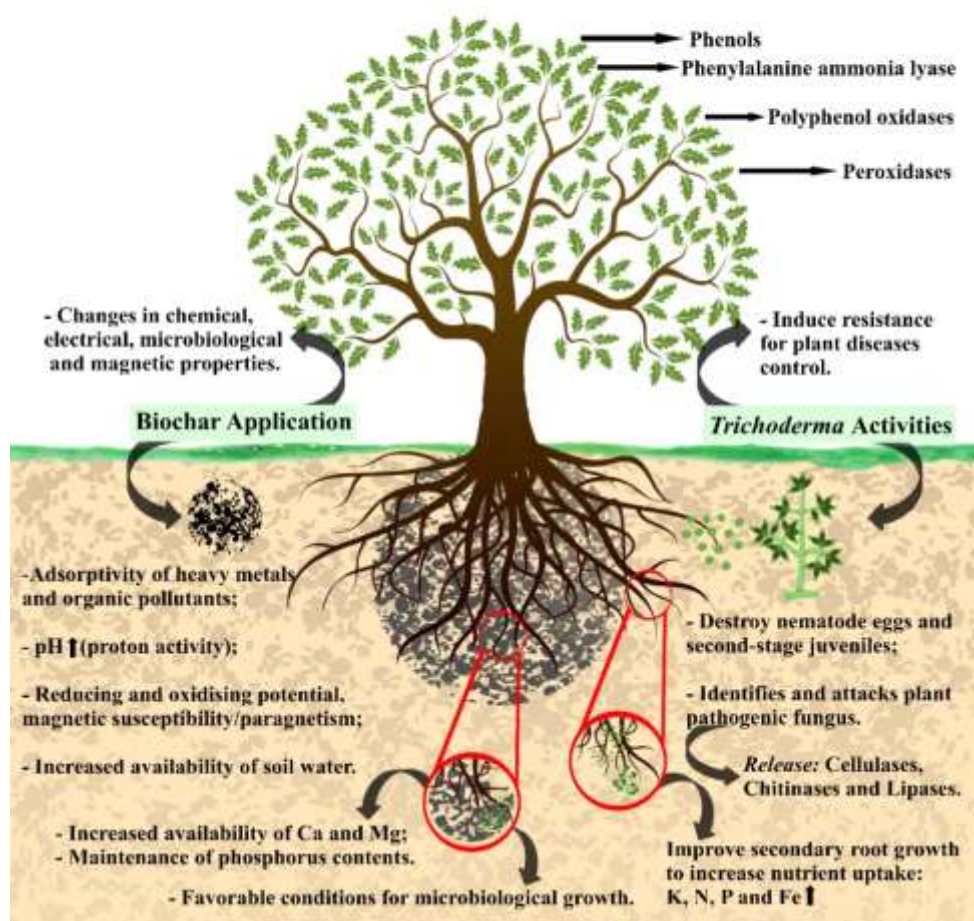
Biochar has been considered an important tool to management of soilborne phytopathogens, due to its origin and production process, biochar has physicochemical properties and beneficial attributes (Medeiros et al., 2021). Biochar is a solid compound, rich in C obtained through the combustion of organic materials and could be produced from several types of raw material, such as agricultural waste, wood, and sewage sludge (Lehmann et al., 2011). The high carbon C in the biochar makes it an excellent source of substrate for microorganisms. Biochar remains in the soil for long periods, improving the physical, chemical, and biological soil attributes (Lima et al., 2018). Moreover, it shows high CEC, raises the pH, and increases water retention in the soil (Foster et al., 2016).

In addition, its high porosity and pore size provide an ideal habitat for the growth of microorganisms, which can ensure greater survival of beneficial microorganisms in the soil (Muter et al., 2017; Jaiswal et al., 2018). For example, the use of biochar changes the soil microbiome and can be as inoculant carrier of bacteria consortium against *Fusarium* sp., as these bacteria remain viable after more than six months of storage (Elhadidy, 2019) and is capable of plant growth promotion due to promote the nutrient availability in the soil. Ajeng et al. (2020) showed that biochar act to the retention of nutrients to avoid being metabolized by other phytopathogenic microorganisms or to leaching. This inputs plays an important role in the selective promotion of functional microorganism to dominate the soil microbial community (Liu et al., 2020), promoted root colonization by native arbuscular mycorrhiza and enriches the microbial network (Ajeng et al. 2020), as *T. aureoviride* (Medeiros et al., 2020b).

3.5 Plant disease control mechanisms by biochar

The (Medeiros et al., 2021) showed in a critical review in which 70% of the studies validated biochar as a strategy to manage diseases caused by pathogens in the soil. Studies show that biochar applied to the soil acts directly or indirectly in suppressing plant disease through mechanisms, such as (i) induction to plant resistance, (ii) sorption of allelopathic and fungitoxic compounds to the plant, (iii) increase of beneficial microorganisms, (iv) changes in the soil attributes that promote health and nutrient availability, and (v) changes of abiotic conditions that provide different management mechanisms for disease suppression (Figure 1).

Figure 1: Mechanisms of *Trichoderma* spp. and biochar for the management of plant diseases caused by soilborne pathogens.



Source: Adapted from Medeiros et al (2021).

3.6 Combined use of *Trichoderma* spp. and biochar in the management of plant diseases caused by soilborne pathogen

A better understanding of the use of biochar from different alternative waste sources with *Trichoderma* spp. (TRI), and the relationship between plant disease and environmental parameters would increase our ability to set priorities. Few studies reported the effects of the co-application of biochar with *Trichoderma*. (Medeiros et al., 2020a) and (Medeiros et al., 2020b) demonstrated the positive effects of the combined use of biochar and *T. aureoviride* on plant growth (melon and watermelon) and on the quality of sandy soils. Muter et al. (2017) observed that biochar applied in combination with *Trichoderma* increased germination and height of corn plants (*Zea mays* L.). Sani et al. (2020) showed that the co-application of biochar with *Trichoderma* promoted synergistically growth and flowering in tomato plants.

The effective growth promotion of antagonistic function of microorganisms against pathogens, as is the case of *Trichoderma* spp., are promoted due to the capacity of biochar to provide substrate and a shelter to these microorganisms, increasing the effectiveness of biological control (Muter et al., 2017). The porous structure of biochar allows the best development of plant roots, improving absorption of water and nutrients as well as significantly increasing biomass uptake to

the entire plant. Biochar allows the increase of nutrients and their bioavailability in the soil. Moreover, *Trichoderma* spp. ensures better absorption and assimilation of these nutrients by the plant, favored by the use of biochar, providing advantages to the soil-plant system (Jaiswal et al., 2018).

The use of biochar and *Trichoderma* spp. promotes agricultural practices in a more sustainable way by reducing the use of synthetic fertilizers, minimizing the use of chemicals for disease control, while reducing the use of inputs to increase agricultural productivity, mitigating the impacts caused to the environment by food production thus producing healthier foods (Figure 1). Overall, our findings expand our knowledge about the reuse of wastes transformed in biochar, an alternative management tool of plant disease and add important information that can be suitable for development of strategy for use in the global health concept.

4. Conclusion

The use of biochar and *Trichoderma* spp. is a potential and low-cost alternative to sustainable agricultural production. Their interaction promotes a series of benefits to soil quality and plant growth, reducing the use of synthetic products, increasing sustainable production and food security. This review showed that the biochar has potential for the formulation of new products, as it enhances the competitive power of *Trichoderma* spp. at the soil. Both can act as a powerful alternative tool to control plant diseases caused by pathogens inhabiting the soil, through different mechanisms. Future research should focus on exploring highly efficient strains, optimizing conditions, and assessing a comprehensive number of waste sources for biochar production as well as their efficacy in field experiments.

Acknowledgments

This work was supported by the CNPq, Conselho Nacional de Desenvolvimento Científico e Tecnológico - Brazil under Grant (process n° 153560/2018-5; 313174/2018-0; 426497/2018-0; 391 307335/2017-8; ONDABCBC: 465764/2014-2 and NEXUS: 441305/2017-2), by the CAPES under Grant (88887.736369/2017-00) and by FACEPE under Grant (APQ-0223-5.01/15; APQ-0419-5.01/15; APQ-0431-5.01/17; APQ-0498-3.07/17).

References

- Ajeng, A. A., Abdullah, R., Ling, T. C., Ismail, S., Lau, B. F., Ong, H. C., & Chang, J. S. (2020). Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. *Environmental Technology & Innovation*, 101168. <https://doi.org/10.1016/j.eti.2020.101168>
- Al-ani, L. K. T., & Albaayit, S. F. A. (2018). Antagonistic of some *Trichoderma* against *Fusarium oxysporum* sp f cubense tropical race 4 (FocTR4). *The Eurasia Proceedings of Science, Engineering & Mathematics*, 2, 35–38.
- Alfiky, A. (2019). Effects of ultraviolet irradiation on the in vitro antagonistic potential of *Trichoderma* spp against soil-borne fungal pathogens. *Heliyon* 5(7), e02111. <https://doi.org/10.1016/j.heliyon.2019.e02111>
- Bettiol, W., Pinto, Z. V., da Silva, J. C., Forner, C., de Faria, M. R., Pacifico, M. G., Costa, L. S. A. S. (2019). Produtos comerciais à base de *Trichoderma* Trichod 1:45.
- Bhandari, D. (2017). Bio-control ability of *Trichoderma* species against spot blotch disease (wheat) causing pathogen *Bipolaris sorokiniana* under in vitro condition. *Journal of Bioscience and Agriculture Research*, 14(02): 1194–1201. <https://doi.org/10.18801/jbar.140217.147>
- Bora, B., & Ali, M. S. (2019). Evaluation of Microbial Antagonists against *Sarocladium oryzae* Causing Sheath Rot Disease of Rice (*Oryza sativa* L.). *International Journal of Current Microbiology and Applied Sciences*, 8(7), 1755–1760. <https://doi.org/10.20546/ijemas.2019.807.208>
- Chagas, L. F. B., Junior, A. F. C., Soares, L. P., & Fidelis, R. R. (2017). *Trichoderma* na promoção do crescimento vegetal. *Journal of Neotropical Agriculture*, 4(3): 97–102. <https://doi.org/10.32404/rean.v4i3.1529>
- Chaudhary, S., Sagar, S., Lal, M., Tomar, A., Kumar, V., & Kumar, M. (2020). Biocontrol and growth enhancement potential of *Trichoderma* spp against *Rhizoctonia solani* causing sheath blight disease in rice. *Journal of Environmental Biology*, 41(5), 1034–1045. <https://doi.org/10.22438/jeb/41/5/MRN-1303>

- Checa, C. O. E., Toro, C. M., & Descanse, V. J. (2017). Antagonism of *Trichoderma* spp. strains against pea (*Pisum sativum* L.) *Fusarium* wilt caused by *Fusarium oxysporum* f. sp. *pisi*. *Acta Agronómica*, 66(3), 442–448.
- Cherkupally, R., Amballa, H., & Reddy, B. N. (2017). In vitro antagonistic activity of *Trichoderma* species against *Fusarium oxysporum* f. sp. *melongenae*. *International Journal of Applied Agricultural Research*, 12(1), 87–95.
- Coelho, L., Reis, M., Guerrero, C., & Dionísio, L. (2020). Use of organic composts to suppress bentgrass diseases in *Agrostis stolonifera*. *Biological control*, 141, 104154. <https://doi.org/10.1016/j.biocontrol.2019.104154>
- Da Silva, J. A. T., de Medeiros, E. V., da Silva, J. M., Tenório, D. D. A., Moreira, K. A., Nascimento, T. C. E. D. S., & Souza-Motta, C. (2016). *Trichoderma aureoviride* URM 5158 and *Trichoderma hamatum* URM 6656 are biocontrol agents that act against cassava root rot through different mechanisms. *Journal of Phytopathology*, 164(11–12), 1003–1011. <https://doi.org/10.1111/jph.12521>
- Dendouga, W., Bouregghda, H., & Belhamra, M. (2016). Biocontrol of wheat *Fusarium* crown and root rot by *Trichoderma* spp. and evaluation of their cell wall degrading enzymes activities. *Acta Phytopathologica et Entomologica Hungarica*, 51(1), 1–12. <https://doi.org/10.1556/038.51.2016>
- Elamathi, E., Malathi, P., Viswanathan, R., & Sundar, A. R. (2018). Expression analysis on mycoparasitism related genes during antagonism of *Trichoderma* with *Colletotrichum falcatum* causing red rot in sugarcane. *Journal of Plant Biochemistry and Biotechnology*, 27(3), 351–361. <https://doi.org/10.1007/s13562-018-0444-z>
- El-Gremi, S. M., Draz, I. S., & Youssef, W. A. E. (2017). Biological control of pathogens associated with kernel black point disease of wheat. *Crop Protection*, 91, 13–19. <http://dx.doi.org/10.1016/j.cropro.2016.08.034>
- Elhadidy, A. E. (2019). Performance of some new bioformulations against tomato fusarium wilt. *Egyptian Journal of Desert Research*, 69(1), 1–19. <http://dx.doi.org/10.21608/ejdr.2019.10162.1022>
- Elshahawy, I. E., & El-Mohamedy, R. S. (2019). Biological control of Pythium damping-off and root-rot diseases of tomato using *Trichoderma* isolates employed alone or in combination. *Journal of Plant Pathology*, 101(3), 597–608. <https://doi.org/10.1007/s42161-019-00248-z>
- Foster, E. J., Hansen, N., Wallenstein, M., & Cotrufo, M. F. (2016). Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system. *Agriculture, Ecosystems & Environment*, 233, 404–414. <https://doi.org/10.1016/j.agee.2016.09.029>
- Galletti, S., Paris, R., & Cianchetta, S. (2020) Selected isolates of *Trichoderma gamsii* induce different pathways of systemic resistance in maize upon *Fusarium verticillioides* challenge. *Microbiological Research*, 233, 126406. <https://doi.org/10.1016/j.micres.2019.126406>
- Ghorbanpour, M., Omidvari, M., Abbaszadeh-Dahaji, P., Omidvar, R., & Kariman, K. (2018). Mechanisms underlying the protective effects of beneficial fungi against plant diseases. *Biological Control*, 117, 147–157. <https://doi.org/10.1016/j.biocontrol.2017.11.006>
- Haddad, P. E., Leite, L. G., Lucon, C. M. M., & Harakava, R. (2017). Selection of *Trichoderma* spp strains for the control of *Sclerotinia sclerotiorum* in soybean. *Pesquisa Agropecuária Brasileira*, 52(12), 1140–1148.
- He, A. L., Jia, Liu., Wang, X. H., Zhang, Q. G., Wei, S., & Jie, C. (2019). Soil application of *Trichoderma asperellum* GDFS1009 granules promotes growth and resistance to *Fusarium graminearum* in maize. *Journal of Integrative Agriculture*, 18(3), 599–606.
- Hirpara, D. G., Gajera, H. P., Hirpara, H. Z., & Golakiya, B. A. (2016). Molecular diversity and fingerprints of *Trichoderma* associated with antagonistic potentials against *Sclerotium rolfsii* Sacc. *Journal of Plant Diseases and Protection*, 124(1), 31–40. <https://doi.org/10.1007/s41348-016-0053-9>
- Hirpara, D. G., Gajera, H. P., Hirpara, H. Z., & Golakiya, B. A. (2017). Antipathy of *Trichoderma* against *Sclerotium rolfsii* Sacc: evaluation of cell wall-degrading enzymatic activities and molecular diversity analysis of antagonists. *Journal of Molecular Microbiology and Biotechnology*, 27(1): 22–28. <https://doi.org/10.1159/000452997>
- Hong, S., Jv, H., Lu, M., Wang, B., Zhao, Y., & Ruan, Y. (2020). Significant decline in banana *Fusarium* wilt disease is associated with soil microbiome reconstruction under chilli pepper-banana rotation. *European Journal of Soil Biology*, 97, 103154. <https://doi.org/10.1016/j.ejsobi.2020.103154>
- Jaiswal, A. K., Elad, Y., Cytryn, E., Graber, E. R., & Frenkel, O. (2018). Activating biochar by manipulating the bacterial and fungal microbiome through pre-conditioning. *New Phytologist*, 219(1), 363–377. <https://doi.org/10.1111/nph.15042>
- Jiang, H., Zhang, L., Zhang, J. Z., Ojaghian, M. R., & Hyde, K. D. (2016). Antagonistic interaction between *Trichoderma asperellum* and *Phytophthora capsici* in vitro. *Journal of Zhejiang University Science B*, 17(4), 271–281. <http://dx.doi.org/10.1631/jzus.B1500243>
- Kazerooni, E. A., Al-Shibli, H., Nasehi, A., & Al-Sadi, A. M. (2020). Endophytic *Enterobacter cloacae* exhibits antagonistic activity against *Pythium* damping-off of cucumber. *Ciência Rural*, 50(8), e20191035. <https://doi.org/10.1590/0103-8478cr20191035>
- Khaled, N., & Taheri, P. (2016). Biocontrol mechanisms of *Trichoderma harzianum* against soybean charcoal rot caused by *Macrophomina phaseolina*. *Journal of Plant Protection Research*, 56(1), 21–31. <https://doi.org/10.1515/jppr-2016-0004>
- Khalili, E., Javed, M. A., Huyop, F., Rayatpanah, S., Jamshidi, S., & Wahab, R. A. (2016). Evaluation of *Trichoderma* isolates as potential biological control agent against soybean charcoal rot disease caused by *Macrophomina phaseolina*. *Biotechnology & Biotechnological Equipment*, 30(3), 479–488. <https://doi.org/10.1080/13102818.2016.1147334>
- Kumar, G., Maharshi, A., Patel, J., Mukherjee, A., Singh, H. B., & Sarma, B. K. (2017). *Trichoderma*: a potential fungal antagonist to control plant diseases. *SATSA Mukhapatra Annual Technical Issue*, 21, 206–218.

- Kuzmanovska, B., Rusevski, R., Jankulovska, M., & Oreshkovikj, K. B. (2018). Antagonistic activity of *Trichoderma asperellum* and *Trichoderma harzianum* against genetically diverse *Botrytis cinerea* isolates. *Chilean Journal of Agricultural Research*, 78(3), 391–399. <http://dx.doi.org/10.4067/S0718-58392018000300391>
- Larkin, R. P., & Brewer, M. T. (2020). Effects of crop rotation and biocontrol amendments on *Rhizoctonia* disease of potato and soil microbial communities. *Agriculture* 10(4), 128. <https://doi.org/10.3390/agriculture10040128>
- Larran, S., Santamarina, S. M. P., Roselló, C. J., Simón, M. R., & Perelló, A. (2020). In vitro antagonistic activity of *Trichoderma harzianum* against *Fusarium sudanense* causing seedling blight and seed rot on wheat. *ACS omega*, 5(36), 23276–23283. <https://doi.org/10.1021/acsomega.0c03090>
- Lee, S., Yap, M., Behringer, G., Hung, R., & Bennett, J. W. (2016). Volatile organic compounds emitted by *Trichoderma* species mediate plant growth. *Fungal Biology and Biotechnology*, 3(1), 1–14. <https://doi.org/10.1186/s40694-016-0025-7>
- 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 & Biochemistry*, 43(9), 1812–1836. <https://doi.org/10.1016/j.soilbio.2011.04.022>
- Li, Y., Sun, R., Yu, J., Saravanakumar, K., & Chen, J. (2016). Antagonistic and biocontrol potential of *Trichoderma asperellum* ZJSX5003 against the maize stalk rot pathogen *Fusarium graminearum*. *Indian Journal of Microbiology Research*, 56(3), 318–327. <https://doi.org/10.1007/s12088-016-0581-9>
- Lima, J. R., de Moraes, S. W., de Medeiros, E. V., Duda, G. P., Corrêa, M. M., Martins Filho, A. P., & Hammecker, C. (2018). Effect of biochar on physicochemical properties of a sandy soil and maize growth in a greenhouse experiment. *Geoderma*, 319, 14–23. <https://doi.org/10.1016/j.geoderma.2017.12.033>
- Liu, J., Ding, Y., Ji, Y., Gao, G., & Wang, Y. (2020). Effect of maize straw biochar on bacterial communities in agricultural soil. *Bulletin of Environmental Contamination and Toxicology*, 104: 333–338. <http://dx.doi.org/10.1007/s00128-020-02793-1>
- Lu, Z. X., Tu, G. P., Zhang, T., Li, Y. Q., Wang, X., H., Zhang, Q. G., & Jie, C. (2020). Screening of antagonistic *Trichoderma* strains and their application for controlling stalk rot in maize. *Journal of Integrative Agriculture*, 19(1), 145–152. [https://doi.org/10.1016/S2095-3119\(19\)62734-6](https://doi.org/10.1016/S2095-3119(19)62734-6)
- Moosa, A., Sahi, S. T., Haq, I. U., Farzand, A., Khan, S. A., & Javaid, K. (2017). Antagonistic potential of *Trichoderma* isolates and manures against *Fusarium* wilt of tomato. *International Journal of Vegetable Science*, 23(3), 207–218. <https://doi.org/10.1080/19315260.2016.1232329>
- Muter, O., Grantina-Ievina, L., Makarenkova, G., Vecstaudza, D., Strikauska, S., Selga, T., & Steiner, C. (2017). Effect of biochar and *Trichoderma* application on fungal diversity and growth of *Zea mays* in a sandy loam soil. *Environmental and Experimental Biology*, 15(4), 289–296. <https://doi.org/10.22364/eeb.15.30>
- Medeiros, E. V., Moraes, M. C., Costa, D. P., Silva, J. S., Oliveira, J. B., José, R. S., & Hammecker, C. (2020a). Biochar and *Trichoderma aureoviride* applied to the sandy soil: effect on soil quality and watermelon growth. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 48(2), 735–751. <https://doi.org/10.15835/nbha48211851>
- Medeiros, E. V., Moraes, M. C. H. S., Costa, D. P., Duda, G. P., Oliveira, J. B., Silva, J. A., Lima, J. R. S., & Hammecker, C. (2020b). Effect of biochar and inoculation with *Trichoderma aureoviride* on melon growth and sandy Entisol quality. *Australian Journal of Crop Science*. 14(06), 971–977. <https://doi.org/10.21475/ajcs.20.14.06.p2302>
- Medeiros, E. V., Lima, N. T., de Sousa Lima, J. R., Pinto, K. M., S., da Costa, D. P., Junior, C. L. F., & Hammecker, C. (2021). Biochar as a strategy to manage plant diseases caused by pathogens inhabiting the soil: a critical review. *Phytoparasitica* 1, 1–14. <https://doi.org/10.1007/s12600-021-00887-y>
- Montiel-Rozas, D. M., M., Hurtado-Navarro, M., Díez-Rojo, M. Á., Pascual, J. A., & Ros, M. (2019). Sustainable alternatives to 1, 3-dichloropropene for controlling root-knot nematodes and fungal pathogens in melon crops in Mediterranean soils: Efficacy and effects on soil quality. *Environmental Pollution*, 247, 1046–1054.
- Nawaz, K., Shahid, A. A., Bengyella, L., Subhani, M. N., Ali, M., Anwar, W., & Ali, S. W. (2018). Diversity of *Trichoderma* species in chili rhizosphere that promote vigor and antagonism against virulent *Phytophthora capsici*. *Scientia Horticulturae*, 239, 242–252. <https://doi.org/10.1016/j.scienta.2018.05.048>
- Nawrocka, J., & Małolepsza, U. (2013). Diversity in plant systemic resistance induced by *Trichoderma*. *Biological control*, 67(2), 149–156. <https://doi.org/10.1016/j.biocontrol.2013.07.005>
- Nwankiti, A. O., & Gwa, V. I. (2018). Evaluation of antagonistic effect of *Trichoderma harzianum* against *Fusarium oxysporum* causal agent of white yam (*Dioscorea rotundata* Poir) tuber rot. *Trends in Technical & Scientific Research*, 1(1), 555554. <https://doi.org/10.19080/TTSR.2018.01.555554>
- Pimentel, M. F., Arnão, E., Warner, A. J., Subedi, A., Rocha, L. F., Srour, A., & Fakhoury, A. M. (2020). *Trichoderma* isolates inhibit *Fusarium virguliforme* growth, reduce root rot, and induce defense-related genes on soybean seedlings. *Plant Disease*, 104(7), 1949–1959. <https://doi.org/10.1094/PDIS-08-19-1676-RE>
- Sallam, N. M., Eraky, A. M., & Sallam, A. (2019). Effect of *Trichoderma* spp on *Fusarium* wilt disease of tomato. *Molecular Biology Reports*, 46(4), 4463–4470. <https://doi.org/10.1007/s11033-019-04901-9>
- Sani, M. N. H., Hasan, M., Uddain, J., & Subramaniam, S. (2020). Impact of application of *Trichoderma* and biochar on growth, productivity and nutritional quality of tomato under reduced NPK fertilization. *Annals of Agricultural Sciences*, 65(1), 107–115. <https://doi.org/10.1016/j.aos.2020.06.003>
- Saravanakumar, K., Li, Y., Yu, C., Wang, Q. Q., Wang, M., Sun, J., & Chen, J. (2017). Effect of *Trichoderma harzianum* on maize rhizosphere microbiome and biocontrol of *Fusarium* Stalk rot. *Scientific Reports*, 7(1), 1–13. <https://doi.org/10.1038/s41598-017-01680-w>

Silva, J. A. T., de Medeiros, E. V., da Silva, J. M., Tenório, D. D. A., Moreira, K. A., da Silva Nascimento, T. C. E., & Souza-Motta, C. (2017). Antagonistic activity of *Trichoderma* spp against *Scytalidium lignicola* CMM 1098 and antioxidant enzymatic activity in cassava. *Phytoparasitica*, 45(2), 219–225. <https://doi.org/10.1007/s12600-017-0578-x>

Silva, C. C. G. D., Medeiros, E. V. D., Fracetto, G. G. M., Fracetto, F. J. C., Martins Filho, A. P., Lima, J. R. D. S., & Hammecker, C. (2021). Coffee waste as an eco-friendly and low-cost alternative for biochar production impacts on sandy soil chemical attributes and microbial gene abundance. *Bragantia*, 80. <https://doi.org/10.1590/1678-4499.20200459>

Stocco, M. C., Mónaco, C. I., Abramoff, C., Lampugnani, G., Salerno, G., Kripelz, N., & Consolo, V. F. (2016). Selection and characterization of Argentine isolates of *Trichoderma harzianum* for effective biocontrol of *Septoria* leaf blotch of wheat. *World Journal of Microbiology & Biotechnology*, 32(3), 49. <https://doi.org/10.1007/s11274-015-1989-9>

Sumida, C. H., Daniel, J. F., Araujo, A. P. C., Peitl, D. C., Abreu, L. M., Dekker, R. F., & Canteri, M. G. (2018). *Trichoderma asperelloides* antagonism to nine *Sclerotinia sclerotiorum* strains and biological control of white mold disease in soybean plants. *Biocontrol Science and Technology*, 28(2), 142–156. <https://doi.org/10.1080/09583157.2018.1430743>

Vinodkumar, S., Indumathi, T., & Nakkeeran, S. (2017). *Trichoderma asperellum* (NVT A2) as a potential antagonist for the management of stem rot in carnation under protected cultivation. *Biological control*, 113, 58–64. <https://doi.org/10.1016/j.biocontrol.2017.07.001>

Wang, K. D., Borrego, E. J., Kenerley, C. M., & Kolomiets, M. V. (2020). Oxylipins other than jasmonic acid are xylem-resident signals regulating systemic resistance induced by *Trichoderma virens* in maize. *The Plant Cell*, 32(1), 166–185. <https://doi.org/10.1105/tpc.19.00487>

Zhang, F., Ge, H., Zhang, F., Guo, N., Wang, Y., Chen, L., & Li, C. (2016). Biocontrol potential of *Trichoderma harzianum* isolate T-aloe against *Sclerotinia sclerotiorum* in soybean. *Plant Physiology and Biochemistry*, 100, 64–74. <http://dx.doi.org/10.1016/j.plaphy.2015.12.017>

Zin, N. A., & Badaluddin, N. A. (2020). Biological functions of *Trichoderma* spp for agriculture applications. *Annals of Agricultural Sciences*, 65(2), 168–178. <http://dx.doi.org/10.1016/j.aos>

Zúñiga-Mendoza, E., & Ceja-Torres, L. F. (2017). *In vitro* antagonism of *Trichoderma harzianum* on *Sclerotium cepivorum* Berk and *S. rolfsii* Sacc, causal agents of onion rot. *Phyton. Inter. Journal of Experimental Botany*, 86, 7–13. <http://dx.doi.org/10.32604/phyton.2017.86.007>