SHST
Horticulture and Forestry Society of Transylvania

Pérez-Álvarez S *et al.* (2022)
Notulae Scientia Biologicae
Volume 14, Issue 4, Article number 11364
DOI:10.15835/nsb14411364
Review Article

NSB
Notulae Scientia Biologicae

Phymatotrichopsis root rot and its biological control in the pecan tree in Mexico

Sandra PÉREZ-ÁLVAREZ[1]*, Eduardo F. HECTOR-ARDISANA[2], Martín DÍAZ-GARCÍA[1], Esteban SÁNCHEZ[3], Edith GARCÍA-RAMÍREZ[1]

[1]*Universidad Autónoma de Chihuahua, Facultad de Ciencias Agrícolas y Forestales, Km 2.5, carretera Delicias-Rosales, campus Delicias, CD. Delicias, Chihuahua, CP 33000, México; spalvarez@yuach.mx (*corresponding author); mdiazg@uach.mx; egarciar@uach.mx;*
[2]*Universidad Técnica de Manabí, Instituto de Posgrado, Portoviejo, CP EC130105, Ecuador; ehectorardisana@gmail.com*
[3]*Centro de Investigación en Alimentación y Desarrollo A.C. Unidad Delicias, Av. 4 Sur 3828, Pablo Gómez, 33088 Delicias, Chihuahua, México; esteban@ciad.mx*

Abstract

In Mexico, phymatotrichopsis root rot is regarded as the most important disease in the pecan tree. Its causative agent is the fungus *Phymatotrichopsis omnivora* (Duggar) Hennebert, and the percentage of diseased trees ranges between 3 to more than 25% in a plantation. Symptoms vary from mild damages to the death of the infected tree. The roots invaded by the fungus die with the consequent reduction of the foliage. Chemical control is one of the most used methods to control this pathogenic fungus, but it is expensive and not very efficient, so it is necessary to try other methods such as antagonistic fungi, resistant varieties, plant extracts, among others that have been shown to have some effectiveness, and to design an integrated management program for the pest. For all the reasons stated, the objective of this review was to address the most current aspects of the disease and its biocontrol in Mexico.

Keywords: antagonistic; chemical control; fungus; root disease

Introduction

The importance of the pecan nut in Mexico is well documented, being Chihuahua the first producing state with 68,500 t, followed by Coahuila (16,800 t) and Sonora (15,000 t) (Comenuez, 2021).

In nut production, diseases are a constraining factor; phymatotrichopsis root rot or Texas root rot, caused by the fungus *Phymatotrichopsis omnivora* (Duggar) Hennebert, is a severe disease that attacks pecan tree [*Carya illinoinensis* (Wangenh.) K. Koch] roots, which when infected and destroyed by the fungus, lead the foliage to dry up and die. The fungus can attack seedlings less than one-year-old up to trees older than 45, being more frequent the death of trees less than seven years old (Hu, 2020).

The opportunity to develop tools for the biological control of phymatotrichopsis root rot is high, since there are several soil microorganisms that are strongly antagonistic to *P. omnivora*, such as the fungus

Received: 19 Oct 2022. Received in revised form: 05 Dec 2022. Accepted: 07 Dec 2022. Published online: 12 Dec 2022.
From Volume 13, Issue 1, 2021, Notulae Scientia Biologicae journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

Trichoderma (Samaniego-Gaxiola *et al*., 2019). According to a recent report, the use of chemical pesticides diminished in 2% per year, and biopesticides application increased to a 15% because of restriction laws (Damalas and Koutroubas, 2018). Agronomic practices based on respect for the environment, which at the same time guarantee the sustainability of farms and income for producers, are the future of agriculture (Fenibo *et al*., 2021).

The present review was done by searching in Google Scholar, Research Gate, PubMed/MEDILINE, Web of Science and Scopus databases, being the aim to give information about the phymatotrichopsis root rot diseases and its control, focusing on disease control with antagonistic fungi. It is important to note that there is not much recent literature on this disease affecting pecan tree.

Pecan tree [*Carya illinoinensis* (Wangenh.) K. Koch]

The pecan tree, commonly called pecan, is a deciduous fruit tree of the Juglandaceae family, genus *Carya* that includes nearly 20 species (Chávez *et al*., 2009) that reaches a height of 75-100 feet tall with a large, typically wide spreading crown (canopy) and a longevity of more than 100 years (Madero, 2000). The reproductive age of these trees begins from the fifth or sixth year. This species is native to Mexico and the United States of America (Orona *et al*., 2007), being Mexico the second largest producer of pecan nuts and the first exporter of this product in the world (Orona-Castillo *et al*., 2019).

In Mexico, the approximate total area of the pecan tree in irrigation conditions was 144,649.50 ha in 2021. The states with the highest pecan nut production at the national level are Chihuahua, Coahuila and Sonora with a total of 92.36%, particularly the states of Chihuahua and Coahuila together contribute 82% of the national nut production (SIAP, 2022).

Pecan is one of the most important horticultural nut crops in the world and the nut has an extraordinary calorific value (~680 calories/100 g kernel). Pecan is better to walnut in quality (8-10% proteins, flavour, 65-70% fats, high in potassium, phosphorous, and vitamins A, C, E and B complex) and succeeds best in the areas which are lower and hotter for nut cultivation (Sparks, 2000; Singh *et al*., 2009).

In addition to the nutritional characteristics that the nut has, the shells of the pecan also have important properties that are useful for industry by-products (Dunford *et al*., 2022). Several studies reported the existence of health-beneficial phytochemicals compounds in pecan shells (do Prado *et al*., 2009; Sevimli-Gur *et al*., 2021). Greater levels of tannins and phenols were found in the shells compare to the edible part of pecans (do Prado *et al*., 2009), those compounds have medicinal and nutritional significance because of their powerful antioxidant properties. Huge amounts of shells produced during the edible process represent about 40 to 50% of the whole nut weight, for this reason pecan nut shelling industry by-products have commercial impact and possible for valorisation (Sevimli-Gur *et al*., 2021; do Prado et al., 2009).

The antioxidant activity of phenolic compounds is associated with preventing the incidence of chronic-degenerative diseases such as arteriosclerosis, Alzheimer's, Parkinson's, obesity, diabetes, cardiovascular problems, cholesterol and some types of cancer (Flores-Córdova *et al*., 2017). In addition, it protects and strengthens the human body, delaying aging by preventing cell oxidation by neutralizing free radicals (Flores-Córdova *et al*., 2021).

Phymatotrichopsis root rot generalities

The disease has been reported in Mexico since 1922, being widely detected in the North and northwest states such as Chihuahua, Sinaloa, Tamaulipas, Sonora, Nuevo León, Durango, Baja California and Baja California Sur (Reyes, 2015).

Phymatotrichopsis root rot is a disease that destroys the roots of pecan trees and other agricultural crops, the causal agent is the fungus *P. omnivora* (Samaniego-Gaxiola *et al*., 2001). The infection is influenced by several physiological and environmental factors, including the maturity of the host, quantity and location of the primary inoculum, soil temperatures and soil texture (Rush *et al*., 1984).

One of the main characteristics of phymatotrichopsis root rot is that the leaves turn brown and wither without previous symptoms (Figure 1), permanent wilting occurs in a couple of days, then the tree dries up, and the leaves remain firmly attached to the plant (Figure 2). At the time of incipient wilting, the roots are already completely invaded by the fungus (Hu, 2020). The cortical tissue of the roots is destroyed, so they will rapidly flake off and they are covered by the mycelium of the fungus. Almond and pecan trees often exhibit a brown colour before wilting and one or several branches of the tree may die even if few roots have been invaded (Goldberg, 2005).

Figure 1. Wilting (bronzing) and leaf necrosis of pecan trees affected by phymatotrichopsis root rot
Source: Authors

Figure 2. Pecan tree that suffered sudden death from phymatotrichopsis root rot, where the brown foliage remains attached for the first few weeks
Source: Authors

Root colonization can occur 14 d before symptoms can be observed (Rush *et al.*, 1984). Alternatively, it has been observed that in pecan trees when the plantation density is high, there is more mortality of the trees, however, according to Samaniego-Gaxiola *et al.* (2014) the presence or development of the disease is closely associated with the susceptibility of the plant to the pathogen.

In aboveground tissues, root rot produces vascular discoloration of the stem and sudden wilting of the leaves, without abscission and eventual death of the plant. Characteristic branching mycelial cords woven by anastomoses around the central hyphae (creamy-yellowish) of the pathogen are typically visible on the root surface, which help diagnosis. Different long tapered hyphae arise from this structure (opposite and at right angles) forming a cruciform figure, an irrefutable taxonomic characteristic. Old trees show decreased growth and vigor (Reyes, 2015).

Generally, plants that acquire diseases caused by pathogens like *Fusarium*, *Rhizoctonia*, *Phymatotrichopsis* and others increase their severity with the time. In the specific case of pecan trees affected by *P. omnivora* is possible that some affected trees show no change in symptoms during four years (Samaniego-Gaxiola *et al*., 2002).

In annual or perennial crops, phymatotrichopsis root rot through the years, expands radially and the area devastated by the disease is called blotch. When the distance of the plants between rows does not favor contagion between plants, the incidence of the disease will be in function of the number of points of infection, multiplied by the average number of diseased plants in each point (Jeger *et al*., 1987).

Taxonomy, ecology, and biology of *P. omnivore*

The major group of plant fungal pathogens are necrotrophic fungi causing substantial crop losses worldwide (Shao *et al*., 2021). *Phymatotrichopsis omnivora* is a soil-borne necrotrophic fungal pathogen that can infects over 2,000 dicotyledonous plants (Kankanala *et al*., 2020). The definition of necrotrophic pathogens is that they kill host plant cells and use nutrients to support their own live. Necrotrophic fungi also may induce apoptosis in host cells rather than breaking plant cell walls, or induce their own apoptosis (Shi *et al*., 2020).

The Index taxonomical identification of the fungus is given in the NCBI database by Schoch *et al*., (2020) as following:

Current scientific name: *Phymatotrichopsis omnivora* (Duggar) Hennebert, 1973
Kingdom: Fungi
Phylum: Ascomycota
Subphylum: Pezizomycotina
Class: Pezizomycetes
Order: Pezizales
Family: Rhizinaceae
Genus: *Phymatotrichopsis*

P. omnivora is a fungus with no known sexual phase, it was named *Phymatotrichum omnivorum* (Shear) because of the conidial characteristics, which are produced in spore mats that grow near the diseased plant (Duggar, 1916). It was found within the class Hyphomycetes, order Hyphales (Moniliales), and was associated within the Phylum Basidiomycota. Hennebert (1973) renamed it *Phymatotrichopsis omnivora* (Duggar) Hennebert, due to the affinity that he observed that this fungus had with Botrytis, within the division Ascomycota. The life cycle of the fungus is represented in Figure 3.

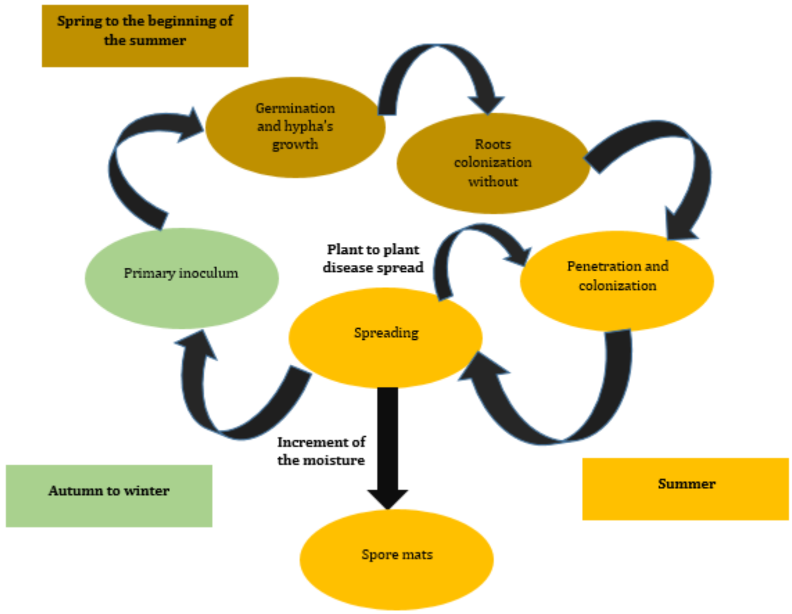

Figure 3. The life cycle of *P. omnivora*
Source: Authors

Kankanala *et al.* (2020) founded that *P. omnivora* infects the susceptible plant as a traditional necrotroph. However, it infects the partially resistant plant as a hemi biotroph triggering salicylic acid-mediated defence pathways in the plant. Further, the infection strategy in partially resistant plants is determined by the host responses during early infection stages.

Agrios (1997) explained that this fungus survives and reproduces by sclerotia or hyphae and by this one the fungus moves through the soil or over the root tissue. It spreads slowly from plant to plant when a fungal thread from an infected root grows through the soil and reaches a healthy root. However, the sclerotia are resistance structures through which the fungus can survive during the winter without a host or when the conditions of the environment are not favourable. Also, these structures can survive for at least five years in the soil (Riggs, 2008) up to 20 years if there are no limiting factors (Samaniego-Gaxiola, 2008).

Reyes (2015) mentioned that for the infection the mycelium, by contacting the roots, invades and penetrates the tissues (Figure 4).

Figure 4. Root of pecan tree infected with *P. omnivora*
Source: Authors

This fungus produces a mass of conidia (white crusty formations) on the soil surface near the host when hot, humid weather prevails. These conidia have been considered sterile, but it is suspected that they may serve to establish new sources of infection. The way that this pathogen penetrates the roots is not yet clear, but the fungus colonizes the interior of this organ, obstructing the vascular system and blocking the movement of water (Riggs, 2008).

Control

The sclerotia of *P. omnivora*, as already mentioned, are capable of living in the soil in adverse periods for many years, making this pathogen control very difficult (Rush *et al*., 1984).

The main control methods are based on integrated crop management, which includes crop rotation, reductive soil disinfestation (Momma *et al*., 2006), elimination of diseased plants, the addition of fertilizers that, in addition to reducing the soil pH, when decomposed, favour the proliferation of populations of microorganisms that can present antagonism to the fungus (Agrios, 1997), chemical control (Martínez-Escudero *et al*., 2016) and biological control (Guigón-López *et al*., 2015).

Reductive soil disinfestation

This is a method where a carbon (C) source such as molasses, wheat straw or carbohydrate-rich compounds are added to the soil, then the soil is saturated with water and covered with a plastic (Momma *et al*., 2006).

According to Samaniego-Gaxiola *et al.* (2019) sclerotia of *P. omnivora* died in supernatants at pH ~4 that came from the soil with 2.0 and 4.0 mg g^{-1} of added glucose. The pH and oxidation-reduction potential reached in soils with glucose and molasses are characteristic of reductive soil disinfestation. Another way of reductive soil disinfestation is to use various substrates as a source of C for the control of a single pathogen (Serrano-Pérez et al., 2017).

An additional experiment demonstrated that after the reductive soil disinfestation was possible to reduce the populations of fungi in soil cultivated with watermelon (*Citrullus lanatus* (Thunb.) Matsum and Nakai) (Liu *et al*., 2018).

Chemical control

For many years, synthetic fungicides have been used as the major control against fungal plant pathogens. Nevertheless, recently, while the chemical method is still predominant over other controls, the application of synthetic fungicides has been gradually diminishing because of the global preoccupation on risks due to residues in soil, water, air and foods (Palmieri *et al*., 2022).

Less success with the application of several chemicals have been achieved; nevertheless, Rush and Lyda (1984) worked with methyl bromide and they found that it was effective but huge amounts of this chemical must be added deeply into the soil, making it costly and consequently not commercially practical.

Even though there is no effective fungicide to control phymatotrichopsis root rot in pecan trees, the chemical flutriafol has been used with effectiveness in controlling *P. omnivora* in cotton (Isakeit et al., 2012). Rhyme is the common name of flutriafol in Arizona and it is used for the control of powdery mildew and scab (foliar fungal diseases) on pecan, but not for the control of phymatotrichopsis root rot (Hu, 2018).

Systemic fungicides, like benzimidazoles and sterol biosynthesis inhibitors, have been used with good results to reduce the incidence of *P. omnivora* (Whitson and Hine, 1986). Because most systemic fungicides are relatively expensive, do not translocate well, and exhibit poor soil penetration and persistence, the efficacy of these products must be prudently evaluated (Uppalapati *et al*., 2010).

Biological control

For plant diseases, biological control is frequently defined as direct or indirect inhibition of the pathogen responsible for the disease or a disease, by another organism or group of them (Cook, 1985). A wider meaning also includes specific metabolites, isolated from interactions or plant extracts (attractant activities or antibiotic) that can be beneficial for controlling diseases (Roberts and Taylor, 2016). Plant pathologists have inclined to use the term to denote control methods including soil pH alterations, crop rotation, use of organic amendments, etc (Baker, 1991).

The influence of oilseed meals [0%, 1%, and 5% (w/w] from both brassicaceous plants including mustard (*Brassica juncea* L.) and camelina (*Camelina sativa* L. Crantz) as well as non-brassicaceous plants including jatropha (*Jatropha curcas* L.), flax (*Linum usitatissimum* L.), and Chinese tallow (*Triadica sebifera* L.) was evaluated on *P. omnivora* sclerotial germination and hyphal growth in Branyon clay soil and as results all tested brassicaceous and jatropha seed meals at 5% and 1% application rates respectively were capable to inhibit *P. omnivora* sclerotial germination and hyphal growth, with mustard seed meal being the best treatment (Hu *et al*., 2011).

Valero-Galván *et al*. (2005) used essential oils produced by plants such as oregano (*Origanum vulgare* L.) in different concentrations (50, 100, 150, 200, 250, 500 ppm) to control *P. omnivora* and they found that when the essential oil was used in concentrations of 150, 200, 250, 500 ppm, the fungus was completely inhibited.

According to Rush and Lyda (1982) another form to control *P. omnivora* was by the application of anhydrous ammonia (NH3) that was toxic to the mycelium and sclerotia of the fungus at 28 μg mL^{-1} and this was proportional to the period of exposure, giving 3, 23, 34, and 59% of kill of sclerotia after 1, 12, 24, and 48 h respectively. Exposure of sclerotia to NH3 concentrations of 42, 56, or 84 μg mL^{-1} for 12 h resulted in 100% control of the pathogen *in vitro* but for the *in-situ* control higher concentrations of NH3 were necessary so 138 and 276 μg g^{-1} resulted in 35 and 79% control, respectively.

Soil microorganisms play an important role in pathogen control because plants through the roots produce exudates that provide a perfect environment for the growth of microorganisms with which the roots establish associations, either for the stimulation of plant growth, exchange of nutrients, or protection against pathogens, and some others (Whipps, 2001; Sarabia *et al.*, 2010).

There are several biocontrol products listed in the Environmental Protection Agency (EPA), and one of the most used microorganisms in the registered products correspond to fungi belonging to the genus *Trichoderma* spp., particularly *T. harzianum*, *T. lignorum* and *T. viride* (Vinchira-Villarraga and Moreno-Sarmiento, 2019). The application of these antagonistic microorganisms is because the mechanisms of action that they use to control pathogens such as mycoparasitism, competition, production of volatile compounds and antibiosis (NawRocka *et al*., 2017; Awad *et al*., 2018).

Trichoderma spp. have the capacity to produce hydrolytic enzymes capable of invading the sclerotia of *P. omnivora*, preventing them from germinating (Samaniego-Gaxiola, 2008; Guigón-López *et al*., 2014; Guigón-López *et al*., 2015).

López et al. (2015) tested three native isolates of *T. asperellum* as antagonists of *P. omnivora*, finding an antagonistic capacity of between 61.4% and 90.1%, with a daily mycelial rate of 2.23 mm. Also, Guigón-López *et al*. (2010) analysed the effect of six *Trichoderma* spp. native strains and they found that *T. asperellum* TC74, T341 and T359 inhibited the *P. omnivora* growth from 28% to 37%.

Commercial plant protection products have been developed that contain special strains of live *Trichoderma* species, primarily *T. harzianum* and have been formulated so that farmers can easily apply them in the field. It is a safe and effective biocontrol agent that can control a variety of fungal (and bacterial) diseases, including wilt, stem rot, and downy mildew (Singh *et al*., 2010).

Molecular research of the topic

Despite the extensive investigation achieved on *P. omnivora* over the past 100 years, several areas of the physiology and molecular biology of this pathogen and its relationship with host plants are still poor understood (Uppalapati *et al*., 2010).

Marek *et al*. (2009) reported the molecular systematics of *P. omnivora* using the ribosomal DNA and RNA polymerase II subunit 2 loci and they confirmed that this fungus belongs to the phylum Ascomycota not Basidiomycota. Also, through this research authors found that the acknowledgement exclusively to Duggar (Hennebert, 1973) was an error because this is in conflict with the 'one fungus one name' definition, and left the taxon without a type specimen. Their proposal was that the attribution should be to Shear (1907), with his type specimen as holotype. The Panel notes that this proposal has not been taken into account by indexfungorum.org and mycobank.org, which still use *P. omnivora* (Duggar) Hennebert.

Macmil (2009) constructed a cDNA library containing expressed genes from the three different structures that characterized distinct morphological stages in the life cycle of *P. omnivora* (mycelia, conidial spore and sclerotia) and on exposure to three different nutrient conditions (media deprived of either carbon or nitrogen; *Medicago truncatula* Gaertn and *Medicago sativa* L. root exudates and non-host root exudates of *Sorghum bicolor* Moench. Unique expressed sequence tags (ESTs) were compared with homologs sequences in GenBank, the Consortium for the functional Genomics of Microbial Eukaryotes (COGEME), Eukaryotic Orthologous Genes (KOG) and Kyoto Encyclopedia of Genes and Genome (KEGG) databases using the Blast alignment program and characterised into groups based on biological function assignment. Results from the genomic sequence showed that the ~74 Mbp assembly was around twice the dimension expected by electrophoretic gel karyotyping from *P. omnivora* protoplasts supporting the theory that this fungus is an obligate heterokaryon with numerous heterokaryotic nuclei. The comparison with several databases allowed the author to found that *P. omnivora* encode greater numbers of heavy metal and calcium transporting P-type ATPases and ABC-type transporters than *Magnaporthe grisea* (T.T. Hebert) M.E. Barr and *Neurospora crassa* Shear&Dodge, 1843, which allow the pathogen to survive in calcareous heavy metal containing soils and on exposure to plant toxins and fungicides.

Microarrays research was developed by Uppalapati *et al*. (2009) to analyse the host defence signals under *P. omnivora* infection and ethylene was induced by ROS (Reactive Oxygen Species) together with the fungus. In this study when roots of *M. truncatula* were infected with the pathogen, chitinases Class I and Class IV, genes involved in ROS generation and phytohormone such as ethylene and jasmonic acid were identified as upregulated genes.

An expression study was done by Guigón-López *et al*. (2015) between *T. asperellum* strains TC74 (great antagonistic capacity) and Th1 (little antagonistic capacity) with *P. omnivora* and as results both strains were capable to express their β-1,3-exoglucanase and chitinases activities when grown on the different carbon sources (*P. omnivora* powdered sclerotium (MM-PO) and in *Agaricus bisporus* (J.E.Lange) Imbach, 1946 plus fiber (MM-AF). Mycoparasitism-related genes were primary expressed when both *T. asperellum* strains were tested with *P. omnivora*.

No molecular study was found in the reviewed literature that refers to the pathogen in the pecan tree but the articles read offer a better understanding about this important fungus and help with the improvement of the management strategies and resistant germplasm to control the disease.

Conclusions

Phymatotrichopsis root rot is the fungal disease that causes the greatest damage to pecan trees in Mexico, with losses that in some cases exceed a third of the plantation. Until now, the most used control methods are reductive soil disinfestation and chemical control; however, the efficiency of these techniques is not high, they require some procedures for their use, they cause contamination in the soil and water, and they are very expensive. In the past two decades, biological control methods have begun to be used in the fight against this disease; the use of essential oils from plants and microorganisms, mainly *Trichoderma* sp., exhibits promising results in inhibiting the development of the fungus, and additional advantages such as its harmlessness to the environment and its low cost, which makes it a viable alternative to conventional chemical methods. Molecular biology has shown incipient results on the pathogen, plant defence mechanisms and host-pathogen interaction, which will undoubtedly support the implementation of these technologies in the future.

Authors' Contributions

SPA and MDG Conceptualization; SPA, EFHA and ES writing original draft; SPA, EFHA and EGR writing, review and editing.

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

Acknowledgements

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Agrios GN (1997). Plant Pathology. Academic Press (4th ed), Florida, USA.

Awad NE, Kassem HA, Hamed MA, El-Feky AM, Elnaggar MA, Mahmoud K, Ali MA (2018). Isolation and characterization of the bioactive metabolites from the soil derived fungus *Trichoderma viride*. Mycology 9:70-80. *https://doi.org/10.1080/21501203.2017.1423126*

Baker R (1991). Diversity in biological control. Crop Protection 10(2):85-94. *https://doi.org/10.1016/0261-2194(91)90054-U*

Chávez EJJ, González L, Valenzuela N, Potisek T MaC, González CG (2009). Morfología, índice y densidad estomática en plántulas de nogal pecanero cultivadas bajo tres niveles de radiación solar [Morphology, index and stomatal density in pecan tree seedlings grown under three levels of solar radiation]. Agrofaz 9(3):85-90.

College of Agriculture and Life Sciences, Tucson, Arizona, USA. Retrieved 2022 December 01 from *https://extension.arizona.edu/sites/extension.arizona.edu/files/pubs/az1814-2020.pdf*

Comenuez (2021). Estimado de producción de nuez pecanera para México [Estimated pecan nut production for Mexico]. Retrieved 2022 October 05 from *http://www.comenuez.com/assets/estimacion_comenuez_2021.pdf*

Cook R (1985). Biological control of plan pathogens: Theory to application. Phytopathology 75(1):25-29.

Damalas CA, Koutroubas SD (2018). Current status and recent development in biopesticides use. Agriculture 8(1):13. *https://doi.org/10.3390/agriculture8010013*

do Prado ACP, Aragão AM, Fettand R, Block JM (2009). Antioxidant properties of pecan nut [*Carya illinoinensis* (Wangenh.) C. Koch] shell infusion. Grasas y Aceites 60:330-335. *https://doi.org/10.3989/gya.107708*

Duggar BM (1916). The Texas root rot fungus and its conidial stage. Annals of the Missouri Botanical Garden 3:11-23. *https://doi.org/10.2307/2990071*

Dunford NT, Gumus ZP, Gur CS (2022). Chemical composition and antioxidant properties of pecan shell water extracts. Antioxidants 11:1127. *https://doi.org/10.3390/antiox11061127*

Fenibo EO, Ijoma GN, Matambo T (2021). Biopesticides in sustainable agriculture: A critical sustainable development driver governed by green chemistry principles. Frontiers in Sustainable Food Systems 5:619058. *https://doi.org/10.3389/fsufs.2021.619058*

Flores-Córdova MA, Rodríguez-Roque MJ, Pérez-Álvarez S, Salas-Salazar NA, Soto-Caballero MC (2021). Importancia de la cáscara de nuez para la producción de fenoles y antioxidantes [Importance of the pecan nut shell for the production of phenols and antioxidants]. Revista Pacana 37:28-30.

Flores-Córdova MA, Sánchez E, Muñoz E, Soto-Parra PR (2017). Phytochemical composition and antioxidant capacity in Mexican pecan nut. Emirates Journal of Food Agriculture 29(5):346-350. *https://doi.org/10.9755/ejfa.EJFA-2016-08-1075*

Goldberg N (2005). Phymatotrichum root rot. New Mexico State University 229:1-4.

Guigón-López C, Guerrero-Prieto V, Lanzuise S, Lorito M (2014). Enzyme activity of extracellular protein induced in *Trichoderma asperellum* and *T. longibrachiatum* by substrates based on *Agaricus bisporus* and *Phymatotrichopsis omnivora*. Fungal Biology 118:211-221. *https://doi.org/10.1016/j.funbio.20*

Guigón-López C, Guerrero-Prieto V, Vargas-Albores F, Carvajal-Millán E, Ávila-Quezada GD, Bravo-Luna L, … Lorito M (2010). Molecular identification of *Trichoderma* spp. strains, *in vitro* growth rate and antagonism against plant pathogen fungi. Revista Mexicana de Fitopatología 28(2):1-12.

Guigón-López C, Vargas-Albores F, Guerrero-Prieto V, Ruocco M, Lorito M (2015). Changes in *Trichoderma asperellum* enzyme expression during parasitism of the cotton root rot pathogen *Phymatotrichopsis omnivora*. Fungal Biology 119:264-273. *https://doi.org/10.1016/j.funbio*

Hennebert GL (1973). Botrytis and Botrytis-like genera. Persoonia 7:183-204.

Hu J (2018). Phymatotrichopsis root rot in pecan. The University of Arizona College of Agriculture and life sciences, Tucson, Arizona. Retrieved 2022 October 10 from *http://www.extension.arizona.edu/pubs/az1771-2018.pdf*

Hu J (2020). Symptom identification of pecan *Phymatotrichopsis root rot* (PRR). The University of Arizona.

Hu P, Wang AS, Engledow AS, Hollister EB, Rothlisberger KL, Matocha JE, … Gentry TJ (2011). Inhibition of the germination and growth of *Phymatotrichopsis omnivora* (cotton root rot) by oilseed meals and isothiocyanates. Applied Soil Ecology 49:68-75. *https://doi.org/10.1016/j.apsoil.2011.06.014*

Isakeit T, Minzenmayer RR, Morgan GD, Drake DR, Mott DA, Fromme DD, Multer WL, … Nichols RL (2012). Flutriafol, a new fungicide for managing root rot of cotton, caused by *Phymatotrichopsis omnivora*, in Texas. In: Annual Meeting Communicating Science. American Phytopathology Society, USA pp 176.

Jeger MJ, Kenerley CM, Gerik TJ, Koch DO (1987). Spatial dynamics of *Phymatotrichum* root in row crops in the Black region of north central Texas. Phytopathology 77:1647-1656.

Kankanala P, Jones P, Sekhar-Nandety R, Jacobson DA, Mysore KS (2020). Plasticity of *Phymatotrichopsis omnivor*a infection strategies is dependent on host and nonhost plant responses. Plant Cell and Environment 43:1084-1101. *https://doi.org/10.1111/pce.13721*

Liu L, Chen S, Zhao J, Zhou X, Wang B, Li Y, Zheng G, Zhang J, Cai Z, Huang X (2018). Watermelon planting is capable to restructure the soil microbiome that regulated by reductive soil disinfestation. Applied Soil Ecology 129:52-60. *https://doi.org/10.1016/j.apsoil.2018.05.004*

López VBE, Armenta BAD, Hernández VS, Apodaca SMA, Samaniego GJA, Leyva MKY, Valdez OA (2015). Selección *in vitro* e identificación de aislados de *Trichoderma* spp. y *Bacillus* spp. nativos para el control de *Phymatotrichopsis omnivora* [*In vitro* selection and identification of isolates of *Trichoderma* spp. and *Bacillus* spp. natives for the control of *Phymatotrichopsis omnivora*]. Revista Ciencias Técnicas Agropecuarias 111(4):310-325.

Macmil S (2009). Sequence and analysis of the *Phymatotrichopsis omnivora* genome and expressed sequence tags. PhD Thesis, The University of Oklahoma, Norman, OK, US.

Madero E (2000). La nuez de pecán. Programa de estudios fenológicos - proyecto PROPECÁN-INTA Delta 2000 [The pecan nut. Phenological studies program – Project PROPECÁN-INTA Delta 2000]. India XXI: 78-82 p.

Marek SM, Hansen K, Romanish M and Thorn RG (2009). Molecular systematics of the cotton root rot pathogen, *Phymatotrichopsis omnivora*. Persoonia 22:63-74. *https://doi.org/10.3767/003158509X430930*

Momma N, Yamamoto K, Simandi P, Shishido M (2006). Role of organic acids in the mechanisms of biological soil disinfestation (BSD). Journal of General Plant Pathology 72(4):247-252. *http://dx.doi.org/10.1007/s10327-006-0274-z*

NawRocka J, Szczech M, MałolepSza U (2017). *Trichoderma atroviride* enhances phenolic synthesis and cucumber protection against *Rhizoctonia solani*. Plant Protection Science 5:17-23.

Orona I, Espinoza J, González G, Murillo B, García J, Santamaría J (2007). Aspectos técnicos y socioeconómicos de la producción de nuez (*Carya iilinoensis*) en la Comarca Lagunera [Technical and socioeconomic aspects of the production of walnut (*Carya iilinoensis*) in the Comarca Lagunera]. Revista Mexicana de Agronegocios 11(20):299-307.

Orona-Castillo I, Sangerman-Jarquín DM, Cervantes-Vázquez MG, Espinoza-Arellano JJ, Núñez-Moreno JH (2019). La producción y comercialización de nuez pecanera en México [The production and commercialization of pecan nuts in Mexico]. Revista Mexicana de Ciencias Agrícolas 10(8): 1797-1808.

Palmieri D, Ianiri G, Del Grosso C, Barone G, De Curtis F, Castoria R, Lima G (2022). Advances and Perspectives in the Use of Biocontrol Agents against Fungal Plant Diseases. Horticulturae 8:577. *https://doi.org/10.3390/horticulturae8070577*

Reyes, C (2015). Pudrición texana - *Phymatotrichopsis omnivora* (=*Phymatotrichum omnivorum*)[Texan root rot - *Phymatotrichopsis omnivora* (=*Phymatotrichum omnivorum*)]. Panorama agro.com, Revista de Agricultura. *https://panorama-agro.com/?p=1782*

Riggs, L. J (2008). Historical information on *Phymatotrichopsis omnivora* (Duggar) Hennebert the root rot fungus. Beltwide Cotton Conferences, Nashville, Tennessee pp 199-200. *http://ncc.confex.com/ncc/2008/techprogram/S1672.HTM*

Roberts MR, Taylor JE (2016). Exploiting plant induced resistance as a route to sustainable crop production. In: Collinge DB (Ed). Biotechnology for plant disease control. Wiley Blackwell New York and London pp 319-339.

Rush CM, Lyda SD (1982). Effects of anhydrous ammonia on mycelium and sclerotia of *Phymatotrichum omnivorum*. Phytopathology 72(8):1084-1089.

Rush CM, Lyda SD (1984). Evaluation of deep-chiseled anhydrous ammonia as a control for *Phymatotrichum omnivorum*. Phytopathology 72:1085-1089.

Rush CM, Lyda SD, Gerik TJ (1984). The relationship between time of cortical senescence and foliar symptom development of Phymatotrichum root rot of cotton. Phytopathology 74:1464-1466.

Samaniego-Gaxiola JA (2008). Germinación y sobrevivencia de esclerocios de *Phymatotrichopsis omnivora* en respuesta a NaOCl y suelo con glucosa [Germination and survival of sclerotia of *Phymatotrichopsis omnivora* in response to NaOCl and soil with glucose]. Agricultura Técnica de México 34(4):375-385.

Samaniego-Gaxiola JA, Fontes-Puebla AA, Tarango-Rivero SH, Pedroza-Sandoval A (2014). Comportamiento de la pudrición texana (*Phymatotrichopsis omnivora*) en vivero de nogales [Behavior of Texas rot (*Phymatotrichopsis omnivora*) in walnut nursery]. Revista Mexicana de Fitopatología 32(1):26-37.

Samaniego-Gaxiola JA, Herrera-Pérez T, Pedroza A, Jiménez F, Chew YI (2002). Fluctuación de la severidad de pudrición texana *Phymatotrichopsis omnivora* (Duggar) Hennebert en nogal pecanero (*Carya illinoenesis* K.) bajo las condiciones de la Comarca Lagunera, México [Fluctuation of the severity of Texas rot *Phymatotrichopsis omnivora* (Duggar) Hennebert in pecan tree (*Carya illinoenesis* K.) under the conditions of the Comarca Lagunera, Mexico]. Revista Mexicana de Fitopatología 21(2):143-151.

Samaniego-Gaxiola JA, Herrera-Pérez T, Pedroza-Sandoval A, Santamaría-Cesar J (2001). Relación entre las condiciones de suelo y manejo de las huertas de nogal pecanero con la dinámica de la pudrición texana [Relationship between soil conditions and management of pecan walnut orchards with the dynamics of Texas root rot]. Revista Mexicana de Fitopatología 19:10-18.

Samaniego-Gaxiola JA, Pedroza-Sandoval A, Chew-Madinaveitia Y, Gaytán-Mascorro A (2019). Reductive disinfestation, soil desiccation and *Trichoderma harzianum* to control *Phymatotrichopsis omnivora* in pecan tree nursery. Mexican Journal of Phytopathology 37(2):287-303. *https://doi.org/10.18781/R.MEX.FIT.1808-7*

Sarabia OM, Madrigal PR, Martínez TM, Carreón AY (2010). Plantas, hongos micorrízicos y bacterias: su compleja red de interacciones [Plants, mycorrhizal fungi and bacteria: their complex web of interactions]. Biológicas 12(1):65-71.

Schoch CL, Ciufo S, Domrachev M, Hotton CL, Kannan S, Khovanskaya R, ... Karsch-Mizrachi I (2020). NCBI Taxonomy: a comprehensive update on curation, resources and tools. Database, (Oxford). *https://doi.org/10.1093/database/baaa062*.

Serrano-Pérez P, Rosskopf E, De Santiago A, Rodríguez-Molina MC (2017). Anaerobic soil disinfestation reduces survival and infectivity of *Phytophthora nicotianae* chlamydospores in pepper. Scientia Horticulturae 215:38-48. *http://dx.doi.org/10.1016/j.scienta.2016.12.003*

Sevimli-Gur C, Gezgin Y, Oz A, Sharqi SA, Gumus ZP, Dunford NT (2021). Biological activity of the extracts from pecan shelling industry byproducts. Transactions of the ASABE 64:869-877. *https://doi.org/10.13031/trans.14439*

Shao D, Smith DL, Kabbage M, Roth MG (2021). Effectors of plant necrotrophic fungi. Frontiers in Plant Science 12:1-14. *https://doi.org/10.3389/fpls.2021.687713*.

Shi X, Qin T, Liu Hi, Wu M, Li J, Shi Y, Gao Y, Ren A (2020). Endophytic fungi activated similar defense strategies of *Achnatherum sibiricum* host to different trophic types of pathogens. Frontiers in Microbiology 11:1607. *https://doi.org/10.3389/fmicb.2020.01607*

SIAP (Servicio de Información Agroalimentaria y Pesquera) (2022). Anuario Estadístico de la Producción Agrícola [Statistical Yearbook of Agricultural Production]. Retrieved 2022 October 07 from *https://nube.siap.gob.mx/cierreagricola/*

Singh D, Gupta RK, Singh M, Sharma VK (2009). Characterization of pecan (*Carya illinoensis*) germplasm of seedling origin through regression and principal component analysis. Indian Journal of Agricultural Sciences 79:324-26.

Singh V, Singh PN, Yadav RL, Awasthi SK, Joshi BB, Singh RK, Lal RJ, Duttamajumder SK (2010). Increasing the efficacy of *Trichoderma harzianum* for nutrient uptake and control of red rot in sugarcane. Journal of Horticulture and Forestry 2:66-71.

Sparks D (2000). Pecan in warm climate. In: Erez A (Ed). Temperate Fruit Crops in Warm Climates. Kluwer Academic Pub the Netherlands pp 381-403.

Uppalapati SR, Marek SM, Lee H-K, Nakashima J, Tang Y, Sledge MK, Dixon RA, Mysore KS (2009). Global gene expression profiling during *Medicago truncatula–Phymatotrichopsis omnivora* interaction reveals a role for jasmonic acid, ethylene, and the flavonoid pathway in disease development. Molecular Plant–Microbe Interaction 22:7-17. *https://doi.org/10.1094/MPMI-22-1-0007*

Uppalapati SR, Young CA, Marek SM, Mysore KS (2010). *Phymatotrichum* (cotton) root rot caused by *Phymatotrichopsis omnivora*: retrospects and prospects. Molecular Plant Pathology 11(3):325-334. *http://dx.doi.org/10.1111/J.1364-3703.2010.00616.X*

Valero-Galván JV, Muñoz LN, Rivera-Chavira BE, Rascón-Cruz Q, Silva-Vázquez R, Nevárez-Morillón VG (2005). Aislamiento y control de cepas de hongos asociados a la pudrición texana por medio de aceites esenciales de orégano mexicano [Isolation and control of fungal strains associated with Texas rot by means of essential oils of Mexican oregano]. In: Proceedings of the XII Congreso Nacional de Biotecnología y Bioingeniería. *http://www.smbb.com.mx/congresos%20smbb/merida05/TRABAJOS/AREA_II/CII-02.pdf*

Vinchira-Villarraga DM, Moreno-Sarmiento N (2019). Control biológico: Camino a la agricultura moderna [Biological control: Path to modern agriculture]. Revista Colombiana de Biotecnología 21:2-5. *https://doi.org/10.15446/rev.colomb.biote.v21n1.80860*

Whipps MJ (2001). Root exudates as mediators of mineral acquisition in low-nutrient environments. Journal of Experimental Botany 52:487-511. *https://doi.org/10.1093/jexbot/52.s*

Whitson RS, Hine RB (1986). Activity of propiconazole and other sterol-inhibiting fungicides against *Phymatotrichum omnivorum*. Plant Disease 70:130-133. *http://dx.doi.org/10.1094/PD-70-130*