Journal of Plant Protection Research ISSN 1427-4345

REVIEW

A review of the efficacy of biofumigation agents in the control of soil-borne plant diseases

El-Sayed Hussein Ziedan*

Plant Pathology Department, National Research Centre (NRC), Dokki, Giza, Egypt

Vol. 62, No. 1: 1–11, 2022

DOI: 10.24425/jppr.2022.140292

Received: June 27, 2021
Accepted: September 09, 2021
Online publication: March 04, 2022

*Corresponding address:
ziedanehe@yahoo.com

Responsible Editor:
Ewa Moliszewska

Abstract

The fumigant pesticide methyl bromide (MB) is no longer used in most countries due to its carcinogenic effects. It is followed by carbon bisulfide and chloropicrin which are the most effective liquid synthetic chemicals in pesticide formulations. They are converted to gas to penetrate soil particles and eliminate plant pests such as insects, weeds, and causal plant diseases of viruses, bacteria, fungi, and nematodes under greenhouse, field and storage conditions. These fumigants are non specific pesticides and highly hazardous to humans, environmental resources, and deplete the ozone layers. Furthermore, increasing the cost of crop production by inceasing the amount of pesticides treatments was increased the cost of research on the alternatives of green pesticides from eco-friendly agents, natural organic soil amendments of organic wastes, green manure, biofumigation crops, compost, and essential oils, as well as formulations, are examples of this. Organic fumigants that are non toxic, non-residual, highly degradable and decomposable are available as eco-friendly alternatives to chemical pesticides to manage soil borne pests and diseases of plants. This article summarizes the development of applicable eco-friendly formulations which use natural organic materials to disinfest soil in order to reduce plant diseases caused by soil--borne pathogens.

Keywords: biofumigation, compost, diseases, essential oils organic amendments

Introduction

The total agricultural losses of economic crops which amount to about 50–75% are caused by soil-borne pathogenic fungi of *Rhizoctonia* spp., *Fusarium* spp., *Verticillium* spp., *Sclerotinia* spp., *Pythium* spp. and *Phytophthora* spp. The losses are due to seed rot, root rot, and wilt diseases in different crop fields and greenhouses (Lewis and Papavizas 1991). Since the last century, methyl bromide (MB) has been the most effective fumigation agent in broad spectrum pesticides. In France, it has been used since the 1930s in agriculture to fumigate soil in both plant nurseries and open fields, as well as greenhouses, for healthy transplants of economic vegetables, fruits, and flowers. In developing countries, MB is part of therapeutic applications to protect against soil-borne plant pests, weeds, and pathogens (Thomas 1996). The main disadvantage of MB application is the depletion of the ozone layer and its dangerous effects on human life. It causes failure of the nervous and respiratory systems, eyes, and skin (Barry *et al.* 2012). Physical solarization methods and hot water alternatives are more expensive and ineffective in a variety of soil conditions (Goud *et al.* 2004). Researchers are constantly developing naturally safe organic materials that are effective alternatives for soil amendments against various plant pathogens that are biodegradable, non-ozone depleting, and enhance plant growth and yield. Classically, the main alternative measures for controlling soil-borne plant pests, pathogens, and weeds involve adding various inorganic and synthetic chemicals, which are hazardous to human health and suppress beneficial microorganisms in the soil (Aktar *et al.* 2009; Markakis *et al.* 2016). This article sheds more light on developing effective, eco-friendly formulations from different natural organic materials and their application in suppressing soil-borne plant pathogens and disease incidence (Cotxarrera *et al.* 2002; Mazzola 2004; Mayo-Prieto *et al.* 2020).

Organic soil amendments for controlling plant soil-borne diseases

Soil amendments with organic agriculture wastes, green manure, animal and food industrial wastes rich in micronutrients, macronutrients, and microorganisms have a positive influence on chemical, physical, and biological soil structures and plant disease incidence caused by pathogenic bacteria, fungi, nematodes, and weeds (Bailey and Lazarovits 2003; Haidar and Sidiahmed 2006). Soil amendment with liquid swine manure reduced Verticillium wilt disease of potatoes by 40% and reduced microsclerotia germination of fungal pathogen *Verticillium dahliae* by 90% (Conn *et al.* 2005). Soil amended with hairy vetch at different rates reduced wilt disease incidence caused by *Fusarium oxysporum* f. sp. *nevium* of watermelon plant, completely suppressing fungal populations in soils, enhancing plant growth, and increasing sugar content in fruit (Zhou 2004). *Brassica* crop residues and seed meal, as a new alternative soil fumigant of MB, have effectively reduced the population of several pathogens from fungi and nematodes in the soil (Zasada and Ferris 2004; Ochiai *et al.* 2007). Application of green brassica manure reduced root rot disease syndromes caused by *Rhizoctonia solani* of landscape and bedding plants. The disease syndromes were decreased by increasing the rate to 4,200 g · m^{-1} with no phytotoxic effects observed on the plant for 4 weeks (Cochran and Rothrock 2015). Application of *Stokeyia indica* and *Solieria robusta* seaweed as soil amendments reduced root rot disease of chili caused by several fungi and root-knot diseases. This is generally caused by *Meloidogyne javanica* and increased plant growth (Sultana *et al.* 2008). Sorghum green manure reduced root-knot from nematode infestation in chard, lettuce and melon due to the release of hydrogen cyanide (Djian-Caporalino *et al.* 2019). Since there are no standard quality parameters for organic amendments, and toxic elements accumulate in inorganic fertilizers, composting is the most appropriate technology for developing organic waste, especially from agricultural and industrial wastes. These are obtained by recycling industrial systems with safe commercial fertilizer formulations which enhance plant growth, productivity, and quality as well as suppress soil-plant disease incidence (Pugliese *et al.* 2015; Bonanomi *et al.* 2018). The data in Table 1 reveal some common soil fungal diseases that were controlled by major composts. Peat moss + + 4 to 20% swine waste compost suppressed fungal

Table 1. The effectiveness of applicable composts against plant diseases caused by soil-borne pathogens

Compost	Disease	Causal pathogen	Host	References
Biocompost of sewage sludge	Fusarium wilt	*Fusarium oxysporum* f. sp. *lycopersici*	tomato	Cotxarrera *et al.* (2002)
Peat moss + swine wastes	pre-emergence damping off	*Pythium ultimum* *Rhizoctonia solani*	cucumber	Diab *et al.* (2003)
Cork, olive mare, grape marc spent mushroom	damping-off	*Rhizoctonia solani*	cucumber	Trillas *et al.* (2006)
Grape marc + extracted olive Press cake olive tree leaves + + olive mill waste water Spent mushroom	Fusarium wilt	*Fusarium oxysporum* f. sp. *radicis lycopersici*	tomato	Ntougias *et al.* (2008)
Winery residues of grape stalks and pomace Tomato pulp, sawdust, chipping wood	Fusarium wilt	*Fusarium oxysporum* f. sp. *radicis cucumerinum*	cucumber	Markakis *et al.* (2016)
	Verticillium wilt	*Verticillium dahliae*	eggplant	
Agro-waste	Fusarium wilt	*Fusarium oxysporum*	roselle	Ng *et al.* (2017)
Vermicompost	Fusarium wilt	*Fusarium oxysporum* f. sp. *lycopersici*	tomato	Zhao *et al.* (2019)
Green composts (V – CV and M – CM)	Phytophthora blight	*Phytophthora capsici*	zucchini	Cucu *et al.* (2020)
Green waste composts: 1. ANT's (V – CV) 2. ANT's (M – CM) 3. ANT's (B – CB) 4. ANT's (V2 – CV2)	root, fruit, foliar and crown rot	*Phytophthora capsici*	summer squash	Bellini *et al.* (2020)

disease of damping-off caused by *Pythium ultimum* and *R. solani* of cucumber (Diab *et al.* 2003). Four composts of cork, olive marc, grape marc, and spent mushroom controlled damping-off on cucumber seedlings caused by *R. solani* (Trillas *et al.* 2006). Fusarium wilt of tomato caused by *F. oxysporum* f. sp. *radicis lycopersici* was controlled by three composts of grape marc + extracted olive, press cake olive tree leaves + + olive mill waste water and spent mushroom compost (Ntougias *et al.* 2008). Furthermore, soil amendment with the compost of *Mentha spicata* L. (spearmint) at the rate of 4 to 8% inhibited the emergence of weeds of *Amaranthus retroflexus* L., *Chenopodium album* L., *Portulaca oleracea* L. and *Datura stramonium* L., which enhanced tomato plant growth and populations of beneficial bacterial and fungal counts in the soil (Chalkos *et al.* 2010). Additionally, Fusarium wilt of cucumber incited by *F. oxysporum* f. sp. *cucumerinum* can be controlled by using composts of winery residues of grape stalks (C) and compost (D) of tomato pulp, sawdust, chipping wood (Markakis *et al.* 2016), and vermicompost (Zhao *et al.* 2019). Several green commercial composts were produced by AgriNewTech s.r.l., Italy. The first involved composting for 6 months and it was named ANT's Compost V – CV. The second had the same content as the previous compost plus fungi of BCA "*Trichoderma* sp. TW2 and it was named ANT's compost M – CM. The third, multi biowastes composted for 4 months was named ANT's Compost B – CB. The fourth was a green compost named NT's compost V2 – CV2 suppressed the major roots, fruits, foliar, and crown rot diseases of summer squash caused by *Phytophthora capsici* (Bellini *et al.* 2020) and Phytophthora blight of zucchini caused by *P. capsici* (Cucu *et al.* 2020). Futhermore, application of composts reduced Phytophthora blight incidence by 50% in zucchini and decreased the count of soil pathogen *P. capsici* and enhanced beneficial microorganisms (Cucu *et al.* 2020). Biofumigant crops are wide broad spectrum like MB on pathogenic microorganisms. At the same time biofumigants are selective for enhancing the growth and populations of beneficial soil microorganisms (Klose *et al.* 2006). The best biofumigation crops include several genera of *Brassica*, *Raphanus*, *Sinapis*, and *Eruca* due to their high content of glucosinolates, which produce isothiocyanates (ITCs) as a nonspecific biocide to numerous insects and pathogen agents as well as plant-parasitic nematodes (Kirkegaard and Sarwar 1998). Additionally, non-glucosinolates containing sulfur, fatty acids, nitriles, and thiocyanates are associated with ITCs which have reduced counts of pests and pathogens in soil (Fahey *et al.* 2001; Matthiessen and Kirkegaard 2006). Application of Brassicaceous plant materials, such as *Brassica hirta* and *M. javanica* by *Brassica juncea,* as amendments to soil suppress parasitic nematodes of *M. javanica* and *Tylenchulus semipenetrans* due to glucosinolate precursors of ITC in the plant materials (Zasada and Ferris 2004). Soil amended by broccoli and Sudan grass reduced pea wilt disease and *V. dahliae* populations. It increased yield (Ochiai *et al.* 2007) in pot experiments with tomato plants with either spearmint or oregano plants incorporated in the soil. The results involved increased chlorophyll content, improved quality of tomato fruits, and suppression of the incidence of fungal wilt diseases of tomato incited by *F. oxysporum*. f. sp. *lycopersici* and *V. dahliae*. In this respect, Gas Chromatography Mass Spectrometry (GC-MS) analyzes the release of several volatile constituents for a long time from soil (Kadoglidou *et al.* 2014). The data in Table 2 indicate that *B. juncea,* followed by *B. oleracea,* were the best biofumigant plants. They widely suppressed major soil diseases caused by various soil-borne pathogens such as bacterial wilt disease caused by *R. solanacearum* of potato (Kirkegaard 2009), of tomato (Pontes *et al.* 2019), fungal diseases of root rot caused by *R. solani* on sugar beets and petunias (Motisi *et al.* 2013; Cochran and Rothrock 2015), Fusarium wilt disease of cucumber caused by *F. oxysporun* f. sp. *cucumerinum* and root-knot nematode caused by *M. incognita* of pepper plant (Ros *et al.* 2016) and *M. incognita* and *M. javanica* on tomato (Daneel *et al.* 2018). Furthermore, the application of a commercial preparation of pellets (BioFence) from *B. carinata* as biofumigants highly suppressed the mycelial growth of *Phytophthora cinnamomi*. They also reduced the germination percentage of chlamydospores and zoospores and the count of *P. cinnamomi* in soil and infection of *Quercus cerri* seedlings (Morales-Rodriguez *et al.* 2016). Recently, biofumigation soil by brown mustard crop had reduced populations of *Meloidogyne* spp. and *Rotylenchulus reniformis* in the soil, as well as reduced galls of root and increased growth of zucchini plants with higher efficacy against *Meloidogyne* spp. than *R. reniformis* (Waisen *et al.* 2020).

Essential oils (EOs), as natural and safe biofumigants, are secondary metabolites in different parts of aromatic plants, i.e., flowers, leaves, stems, roots, and seeds. They are extracted by different methods, especially through steam distillation. Essential oils are rich in antioxidants, and are antiviral, insecticidal, antimicrobial, and antifungal. They can be safely used in food preservation and in several medicinal applications. Their fragrance can decrease depression, and improve moods (Irshad *et al.* 2018; Yener 2020). Phytotoxic oils and their compounds, monoterpenes, depend on chemical their composition, and concentrations interfere with electron flow in respiration. They affect cell division, damage cell membranes, and decrease

Table 2. Effective of applicable biofumigation crops against plant diseases caused by soil-borne pathogens

Biofumigants crops	Disease	Causal pathogen	Host	References
Brassica juncea	bacterial wilt	*Ralstonia solanacearum*	potato	Kirkegaard (2009)
			tomato	Pontes *et al.* (2019)
	root-rot	*Rhizoctonia solani*	sugar beet	Motisi *et al.* (2013)
			petunias	Cochran and Rothrock (2015)
			bean	Abdallah *et al.* (2020)
	Fusarium wilt	*F. oxysporum* f. sp. *cucumerinum*	cucumber	Jin *et al.* (2019)
	root-knot	*Meloidogyne incognita*	tomato	Oliveira *et al.* (2011)
		Meloidogyne incognita	pepper	Ros *et al.* (2016)
		Meloidogyne incognita, M. javanica	tomato, potato	Daneel *et al.* (2018)
Brassica oleracea	bacterial wilt	*Ralstonia solanacearum*	potato	Kirkegaard (2009)
			ginger	Bandyopadhyay and Khalko (2016)
Raphanus sativus	bacterial wilt	*Ralstonia solanacearum*	potato	Kirkegaard (2009)
	root-knot	*Meloidogyne incognita*	pepper	Aissani *et al.* (2015) Ros *et al.* (2016)
		Meloidogyne arenaria	tomato	Aydinli and Mennan (2018)
		Meloidogyne incognita, M. javanica	tomato, potato	Daneel *et al.* (2018)
Eruca sativa	root-knot	*Meloidogyne arenaria*	tomato	Aydinli and Mennan (2018)
		Meloidogyne incognita, M. javanica	tomato, potato	Daneel *et al.* (2018)
Brassica carinata	root-rot	*Fusarium* spp.	wheat	Campanella *et al.* (2020)
Sinaps alba	root-knot	*Meloidogyne incognita*	pepper	Ros *et al.* (2016)
Brown mustard	root-knot	*Meloidogyne* spp., *Rotylenchulus reniformis*	zucchini	Waisen *et al.* (2020)
Diplotaxis tenuifolia	Fusarium wilt	*F. oxysporum* f. sp. *cucumerinum*	cucumber	Jin *et al.* (2019)

chlorophyll a and b (Singh *et al.* 2006; Kaur *et al.* 2011). The essential oil of *Phenopodium ambrosisides* completely suppresses the mycelial growth of *R. solani at* 100 ppm, with no phytotoxicity in the germination of seeds and seedling development of *Phaseolus aureus* (Okwute 2012). Neem essential oil more than the rate at 0.5%, had phytotoxic effects which induce chlorosis and stunting (Abbasi *et al.* 2003). In this manner, lemon essential oil up to 3% showed phytotoxic of leaves and roots on corn plant (Hollingsworth 2005). Thyme and cotton lavender EOs seem promising herbicides due to their lower phytotoxicity to major cereal and vegetable crops (Benchaa *et al.* 2019). The greatest herbicidal activity of EOs containing high concentrations of carvacrol, carvone, thymol, linalool, and terpinen-4-ol causes the highest reduction of the weed Bristly foxtail (Koiou *et al.* 2020). Essential oils have contact and fumigant actions on certain pests against a broad spectrum of various problems in the laboratory, greenhouse, field, and during storage. They also have viral, bacterial, and fungal actions and affect insects, weeds, and nematodes (Pradhanang *et al.* 2003; El-Gizawy *et al.* 2018; Benchaa *et al.* 2019; Perczak *et al.* 2019; Eljazi *et al.* 2020; Eloh *et al.* 2020).

Soil bacterial diseases

Bacterial wilt disease, caused by *Ralstonia solanacearum,* is common in open-field vegetable crops worldwide, and in greenhouse cultivation. Several EOs are applicable to soil amendments in the greenhouse for controlling bacterial wilt and their pathogens, as shown in Table 3. In this respect, thymol, palmarosa, and lemongrass EOs as fumigants at the rate of 400–700 mg · l^{-1}, completely suppressed (100%) bacterial wilt disease of tomato caused by *R. solanacearum* and highly reduced the bacterial count in the soil for 7 days after treatments (Pradhanang *et al.* 2003). Application of EOs of thymol and palmarosa was earlier reported for the management of wilt disease of tomato caused by *R. solanacearum* with higher effects of thymol than palmarosa oil (Ji *et al.* 2005). Palmarosa and lemongrass EOs, as biofumigants, reduced wilt disease of edible ginger (*Zingiber officinale*), the count and growth of *R. solanacearum* race 4, and caused the deterioration of bacterial cell shape from 95 to 100%. Meanwhile, eucalyptus oil had bacteriostatic effects with no adverse effects on growth

Table 3. The effective of applicable essential oils as soil amendments on plant diseases caused by soil-borne pathogens

Disease and pathogen	Essential oils	Host	References
	Bacteria diseases		
Bacterial wilt (*Ralstonia solanacearum*)	thymol palmarosa lemongrass	tomato	Pradhanang *et al.* (2003)
	thymol palmarosa	tomato	Ji *et al.* (2005)
	clove	tomato geranium	Huang and Lakshman (2010)
	palmarosa	sweet pepper	Alves *et al.* (2014)
	palmarosa	tomato	Deberdt *et al.* (2018)
	Fungal diseases		
Fusarium wilt (*F. oxysporum* f. sp. *lycopersici*)	thyme	tomato	Ben-Jabeur *et al.* (2015)
	clove mint	tomato	Selim *et al.* (2020)
	oregano spearmint	tomato	Kadoglidou *et al.* (2020)
Fusarium wilt (*F. oxysporum* f. sp. *ciceris*)	thyme lemongrass laurell	chickpea	Moutassem *et al.* (2019)
	Nematode diseases		
Root-knot nematode (*Meloidogyne incognita*)	*Eruca sativa*	tomato	Aissani *et al.* (2015)
	Artemisa absinthium *Lavandula officinalis* *Mentha arvensis*	tomato	Ozdemir and Gozel (2018)
	clove + citronella	ginger	Djiwanti *et al.* (2019)

or yield of ginger (Paret *et al.* 2010), on tomato and geranium plants under greenhouse conditions clove oil reduced bacterial wilt caused by *R. solanacearum* (Huang and Lakshman 2020), bacterial wilt of sweet pepper also caused by *R. solanacearum* was reduced by soil biofumigation with palmarosa essential oil in the greenhouse and in the field (Alves *et al.* 2014). *Pimenta racemosa* var. *racemosa* essential oil controlled bacterial wilt of tomato caused by *R. solanacearum* (Deberdt *et al.* 2018).

Soil fungal diseases

Fusarium wilt, and root rot diseases are widely spread in various geographic regions in the world, causing high losses in yield production of different crops, as shown in Table 3. Essential oils of oregano and spearmint, as well as their constituents carvacrol and carvone, have the strongest inhibitory activity on mycelial growth and conidial production of *Aspergillus terreus, Fusarium oxysporum, Penicillium expansum* and *Verticillium dahliae,* which were isolated from tomato plants (Kadoglidou *et al.* 2011). The essential oil of orange inhibited mycelial growth of toxigenic fungi *F. graminearum* and *F. culmorum* in wheat grain and reduced their mycotoxic concentrations of zearalenone and group B trichothecenes (Perczak *et al.* 2019). Essential oil of *Mentha rotundifolia,* in liquid and vapor phases, was fungicidal to *F. culmorum,* which causes mold in stored cereal grains due to three main components i.e., piperitenone oxide (35.49%), caryophyllene oxide (35.27%) and (10.95%) *cis*-cinerolone (Yakhlef *et al.* 2020). Fusarium wilt and root rot diseases of tomato are the most epidemic worldwide, as shown in Table 3. The most effective EOs for controlling these diseases were clove and mint (Ben-Jabeur *et al.* 2015; Selim *et al.* 2020) and thyme oil on Fusarium wilt of chickpea caused by *F. oxysporum* f. sp. *ciceris* (Kadoglidou *et al.* 2020). Recently, in greenhouse experiments, a soil amendment of 500 ml at 4% of black seed essential oil at sowing date reduced fungal root rot incidence, disease severity, and enhanced morphological characteristics of grapevine plants (Ziedan *et al.* 2020).

Soil nematode diseases

The highly powerful nematicidal activity of EOs against plant parasitic nematodes of root-knot of *M. incognita* and *Caenorhabditis elegans* is due to the monoterpenoid components of carvacrol, thymol, nerolidol and α-terpinene (Oka *et al.* 2000; Echeverrigaray *et al.* 2010; Abdel Rahman *et al.* 2013). Volatilome of *Eruca sativa* was effective against root-knot nematode incidence by *M. incoginta* and enhanced plant growth (Aissani *et al.* 2015). Essential oils of clove and flower extracts of *Foeniculum vulgare* significantly reduced hatching activity by less than 8 and 25%, respectively, at the the rate of 1 mg · l^{-1} (Ibrahim *et al.* 2006). Additionally, as shown in Table 3, EOs of *Corymbia citriodora* and *Eucalyptus camaldulensis* had toxic effects on *M. incognita* under laboratory conditions (El-Baha *et al.* 2017). Furthermore, crucial oils of *Artemisia absinthium, Lavandula officinalis,* and *Mentha arvensis* were highly effective at different concentrations ranging from 1 to 5% against root-knot nematode in tomato plants grown in a greenhouse (Ozdemir and Gozel 2018). Recently, a formulation of citronella and clove oils was more effective than individual EOs on root-knot disease by *Meloidogyne* sp. on ginger (Djiwanti *et al.* 2019). Additionally, EOs *Ocimum sanctum* L.*, Cymbopogon schoenanthus* (L.), Spreng and *Cinnamomum zeylanicum* Blume, and their active components of cinnamyl acetate, methyl eugenol, cinnamyl alcohol, acetyl eugenol, isoeugenol, eugenol, and benzyl benzoate were effective against root-knot nematode incidence (Eloh *et al.* 2020).

Mechanisms of organic soil amendments on soil borne pathogens

Volatile release

During organic matter decomposition in soil various toxic volatile substances are released at high concentrations including formic, acetic and propionic acids which kill microsclerotia of *V. dahliae* the causal fungi of vascular wilt on several plants (Conn *et al.* 2005). Also, hydrogen cyanide (HCN), a biofumigant against the root-knot nematode *M. incognita*, was released from green manure of sorghum during soil degradation (Djian-Caporalino *et al.* 2019). In this manner, in greenhouse experiments, soil amendement at sowing time with 1% of propionic acid solution reduced root rot disease incidence of grapevine in the soil artificially infested by pathogenic fungi of *Fusarium* spp. and *Botryodiplodia theobromae* and enhanced the morphological characteristics of grapevine plants (Ziedan *et al.* 2020).

Acidity of soil (pH)

Soil acidity (pH) changes as organic materials degrade to ammonia, which is released in alkaline soil and in acidic soil, nitrous acids. Nitrous acid has a strong antimicrobial effect on pathogens (Lazarovits *et al.* 2005). Volatile acetic and butyric acids increase the number and activity of several beneficial bacteria that fix nitrogen, such as *Clostridium* sp. and *Enterobacter* sp., which improve plant growth (Okazaki and Nose 1986; Momma *et al.* 2006).

Enhancing beneficial microbial communities

Organic fertilizers are suitable media for maintenance and increase the shelf-life of bacterial count by more than one year (Stella *et al.* 2019). The primary mechanisms of organic soil amendments indirectly increase the total count of various microbial communities of yeasts, fungi, and bacteria in different soils. As a result of various biological mechanisms such as competition, antibiosis, parasitism, and antagonism, they induce suppressive bacterial and fungal vascular wilt pathogens of tomato plant *F. oxysporum* f. sp. *lycopersici* and *R. solanacearum* that causes vascular wilt diseases of tomato (Bailey and Lazarovits 2003; Lazarovits *et al.* 2005; Köhl *et al.* 2019).

Applying various types of organic matter in the seedbed and root distribution zone increased plant growth and promoted microbial communities in the rhizoplane and rhizosphere. *Bacillus* spp., *Enterobacter* spp., *Pseudomonas* spp., *Streptomyces* spp., *Penicillium* spp., and *Trichoderma* spp. compete, parasitize, and inhibit the causal plant pathogens, induce systemic resistance in plants and enhance plant growth (Hoitink *et al.* 1997; Hoitink and Boehm 1999; Chen and Nelson 2008; Pugliese *et al.* 2011; Bonanomi *et al.* 2018; Cucu *et al.* 2019). Furthermore, they produced various plant growth hormones of indol acetic acid (IAA), gibberellic acid (GA), cytokines (CY), siderophores, HCN, fix nitrogen and several hydrolytic enzymes for solubilization of phosphorus, potassium and zinc (Kour *et al.* 2020). Strains of plant growth promotion bacteria (PGPR) *Pseudomonas putida*, *Alcaligenes* sp., *Klebsiella* sp., and *Pseudomonas cedrina* enhance tolerance of *Medicago sativa* to salinity stress in soil (Tirry *et al.* 2021).

Soil biofumigation

Soil amendement with biofumigant crops such as *B. rapa* and *B. napus,* which contain a high level of glucosinolates, were degraded to ITCs. They were slowly released into the soil as volatile gases with toxic properties of weeds, fungi, insects and nematodes (Kirkegaard and Sarwar 1998). They also enhanced, beneficial microbial biocontrol agents such as *Trichoderma* which show high tolerance to isothiocyanates (Smith and Kirkegaard 2002; Galletti *et al*. 2008; Gimsing and Kirkegaard 2009). The high content of phenolic compounds of flavonoids, phenolics, and terpenoids of marjoram and rosemary reduced nematode egg hatching and egg masses on sunflower roots and significantly increased fresh and dry weights of sunflower plants (Abdel Rahman *et al*. 2013, 2019). Furthermore, *Brassica* is a natural source of biofumigants which help to reduce pathogen populations. Their action suppressed sporulation and dormancy structures, like chlamydospores and sclerotia (Kadoglidou *et al*. 2011; Panth *et al*. 2020).

The biofumagation effects of EOs on soil-borne pathogens of plants, bacteria, fungi and nematodes are mainly due to volatile components which quickly penetrate plant tissue and soil particles such as mono terpens, benzene derivatives, hydrocarbons, and others (Khater 2012). Monoterpens are the major components of oils with cytotoxic action on plants and pests. Carvacrol and thymol oils have the most antifungal activity (Nerio *et al*. 2009). Additionally, the malformation of fungal morphology was observed by light and scanning electron microscopy (SEM) examination of mycelial hyphae and sclerotia of *Sclerotinia sclerotiorum* by fennel and oregano EOs as contact and volatile phases. The malformations included mycelial hyphal diameters, cytoplasmic coagulation, necrosis, lysis on hyphae, and alterations on surfaces of rind globular cells, including shriveling and lysis sclerotia (Soylu *et al*. 2007). The deterioration of the cell membrane by inhibition ergosterol synthesis, inhibition of mitochondrial electron transport, interference with the synthesis of protein and RNA or DNA (Lagrouh *et al*. 2017; Nazzaro *et al*. 2017) were also seen. Finally, the cell wall dissolved and death occurred (Lagrouh *et al*. 2017; Bouyaha *et al*. 2019). EOs of carvacrol and thymol damaged the nematode nervous system (Lei *et al*. 2010). Meanwhile, geraniol and citronellol disrupted the permeability of the cell membrane (Oka *et al*. 2000; Bakkali *et al*. 2008).

Integrated applications of organic soil amendments aganist soil-borne diseases

Applying different integration methods of safe available organic physical and biotic agents can result in short and long term management of soil-borne pests, pathogens, weeds and nematodes (Chellemi *et al*. 2016). The combination of organic soil amendments and solarization application has the potential of being a long-term alternative to MB and other synthetic fumigant chemicals in the USA (Ozores-Hampton *et al*. 2005). In Turkey, the combined treatment of soil drenches with chicken manure then solarization application was effective for managing root diseases of strawberries (Benlioğlu *et al*. 2005). Furthermore, soil amendments with green waste of aromatic plants combined with compost enhanced soil fertility and provided toxic action against weeds (Vasilakoglou *et al*. 2007; Dhima *et al*. 2009; Chalkos *et al*. 2010; Kadoglidou *et al*. 2014). The preparation of bio compost is more effective than a single compost and can be a biocontrol agent for suppressing soil-borne pathogens. In this respect, amendment composts of sewage sludge and peat mix with isolates of *Trichoderma asperellum* were highly effective as a new biocontrol alternative against Fusarium wilt disease of tomato (Cotxarrera *et al*. 2002). In this manner Galletti *et al*. (2008) reported that *Trichoderma* spp. are tolerant of some biofumigant crops of *B. oleracea*. The organic amendment of cornmeal improved colonization for a long time. It was an effective biocontrol agent of *T. harzianum* to suppress growth and pathogenicity of *R. solani* inciting root and hypocotyl diseases of beans and increased vegetative and dry weights of the bean shoot system (Mayo-Prieto *et al*. 2020). Recently, formulations of citronella grass oil + salicylic acid followed by clove + + citronella were highly effective on root-knot disease, *Meloidogyne* sp. on ginger (Djiwanti *et al*. 2019). As a result, developing eco-friendly commercial product formulations of different organic wastes, plant extracts and effective biocontrol agents for soil amendment has become critical for sustainable management of plant diseases and pests, as well as the production of healthy food for human consumption and animal feeding.

Conclusions

According to the Montreal protocol, methyl bromide, a standard pesticide that funugated soil against activities of microorganisms, pests, and animals was phased out as the main agent of ozone depletion in January 2005. The development of natural, organic and environmentaly friendly alternatives to methyl bromide is necessary. Different organic materials with high levels of safety, as well as their development as effective commercial formulations, will improve plant growth, productivity and sustainable management of plant diseases.

References

Abbasi P.A., Cuppels D.A., Lazarovits G. 2003. Effect of foliar applications of neem oil and fish emulsion on bacterial spot and yield of tomatoes and peppers. Candian Journal of Plant Pathology 25: 41–48. DOI: 10.1080/07060660309507048

Abdallah I., Yehia R., Kandil M.A. 2020. Biofumigation potential of Indian mustard (*Brassica juncea*) to manage *Rhizoctonia solani*. Egyptian Journal of Biological Pest Control 30: 99. DOI: https://doi.org/10.1186/s41938-020-00297-y

Abdel Rahman F.H., Alaniz N.M., Saleh M.A. 2013. Nematicidal activity of terpenoids. Journal of Enviromental Science and Health, Part B 48: 16–22. DOI: 10.1080/03601234.012.716686

Abdel-Rahman A.A., Kesba H.H., Al-Sayed A.A. 2019. Activity and reproductive capability of *Meloidogyne incognita* and sunflower growth response as influenced by root exudates of some medicinal plants. Biocatalysis and Agricultural Biotechnology 22: 101–418. DOI: https://doi.org/10.1016/j.bcab.2019.101418

Aissani N., Urgeghe P.P., Oplos C., Saba M., Tocco G.,. Petreeto G.L., Eloh K., Urania Menkissoglu-Spiroudi U., Ntalli N., Caboni P. 2015. Nematicidal activity of the volatilome of *Eruca sativa* on *Meloidogyne incognita*. Journal of Agricultural and Food Chemistry 63: 6120–6125. DOI: 10.1021/acs.jafc.5b02425

Alves A.O., Santos M.M.B., Santos T.C.G., Souza E.B., Mariano R.L.R. 2014. Biofumigation with essential oils for managing bacterial wilt of sweet peppers. Journal of Plant Pathology 96: 363–367. DOI: 10.4454/JPP.V96I2.046

Aydinli G., Mennan S. 2018. Biofumigation studies by using *Raphanus sativus* and *Eruca sativa* as a winter cycle crops to control root-knot nematodes. Brazilian Archives of Biology and Technology 61: e18180249. DOI: https://doi.org/10.1590/1678-4324-2018180249

Bailey K.L., Lazarovits G. 2003. Suppressing soil borne diseases with residue management and organic amendments. Soil and Tillage Research 72: 169–180. DOI: 10.1016/S0167-1987(03)00086-2

Bakkali F., Averbeck S., Averbeck D., Idaomar M. 2008. Biological effects of EOs-a review. Food Chemical Toxicology 46: 446–475. DOI: 10.1016/j.fct.2007.09.106

Bandyopadhyay S., Khalko S. 2016. Biofumigation – an eco-friendly approach for managing bacterial wilt and soft rot disease of ginger. Indian Phytopathology 69: 53–56. DOI: http://epubs.icar.org.in/ejournal/index.php/IPPJ/article/viewFile/58001/24232

Barry K.H., Koutros S., Lubin J.H., Coble J.B., Barone-Adesi F., Freeman L.E.B., Sandler D.P., Hoppin G.A., Ma X., Zheng T., Alavanja M.C.R. 2012. Methyl bromide exposure and cancer risk in the agricultural health study. Cancer Causes Control 23: 807–818. DOI: 10.1007/s10552-012-9949-2

Bellini A., Ferrocino I., Cucu A., Pugliese M., Garibaldi A., Gullino M.L. 2020. A compost treatment acts as a suppressive agent in *Phytophthora capsici* – cucurbita pepo pathosystem by modifying the rhizosphere microbiota. Frontiers in Plant Science 11: 885. DOI: doi.org/10.3389/fpls.2020.00885

Benchaa S., Hazzit M., Zermane N., Abdelkrim H. 2019. Chemical composition and herbicidal activity of essential oils from two Labiatae species from Algeria. Journal of Essential Oil Research 31: 335–346. DOI: https://doi.org/10.1080/10412905.2019.1567400

Ben-Jabeur M., Ghabri E., Myriam M., Hamada W. 2015. Thyme essential oil as a defense inducer of tomato against gray mold and Fusarium wilt. Plant Physiology and Biochemistry 94: 35–40. DOI: 10.1016/j.plaphy.2015.05.006

Benlioğlu S., Boz Ö., Yildiz A., Kaşkavalci G., Benlioğlu K. 2005. Alternative soil solarization treatments for the control of soil borne diseases and weeds of strawberry in the Western Anatolia of Turkey. Journal of Phytopathology 153: 423–430. DOI: https://doi.org/10.1111/j.1439-0434.2005.00995.x

Bonanomi G., Lorito M., Vinale F., Woo S.L. 2018. Organic amendments, beneficial microbes, and soil microbiota: toward a unified framework for disease suppression. Annual Review of Phytopathology 56: 1–20. DOI: https://doi.org/10.1146/annurev-080615-100046.

Bouyaha A., Abrini J., Dakka N., Bakri Y. 2019. Essential oils of *Origanum compactum* increase membrane permeability, disturb cell membrane integrity, and suppress quorum-sensing phenotype in bacteria. Journal of Pharmaceutical Analysis 9: 301–311. DOI: https://doi.org/10.1016/j.jpha.2019.03.001

Campanella V., Mandalà C., Angileri V., Miceli C. 2020. Management of common root rot and Fusarium foot rot of wheat using *Brassica carinata* break crop green manure. Crop Protection 130: 105073. DOI: 10.1016/j.cropro.2019.105073

Chalkos D., Kadoglidou K., Karamanoli K., Fotiou C., Pavlatou-Ve A.S., Eleftherohorinos I.G., Constantinidou H.A., Vokou D. 2010. *Mentha spicata* and *Salvia fruticosa* composts as soil amendments in tomato cultivation. Plant Soil 332: 495–509. DOI: 10.1007/s11104-010-0315-4

Chellemi D.O., Gamliel A., Katan J., Subbarao K.V. 2016. Development and deployment of system-based approaches for the management of soilborne plant pathogens. Phytopathology 106: 216–225. DOI: https://doi.org/10.1094/PHYTO-09-15-0204-RVW

Chen M.H., Nelson E.B. 2008. Seed-colonizing microbes from municipal biosolids compost suppress *Pythium ultimum* damping-off on different plant species. Phytopathology 98: 1012–1018. DOI: 10.1094/PHYTO-98-9-1012

Cochran K.A., Rothrock C.S. 2015. Brassica green manure amendments for management of *Rhizoctonia solani* in two annual ornamental crops in the field. HortScience 50: 555–558. DOI: https://doi.org/10.21273/HORTSCI.50.4.555

Conn K.L., Tenuta M., Lazarovits G. 2005. Liquid swine manure can kill *Verticillium dahliae* microsclerotia in soil by volatile fatty acid, nitrous acid, and ammonia toxicity. Phytopathology 95: 28–35. DOI: https://doi.org/10.1094/PHYTO-95-0028

Cotxarrera L., Trillas-Gay M.I., Steinberg C., Alabouvette C. 2002. Use of sewage sludge compost and *Trichoderma asperellum* isolates to suppress Fusarium wilt of tomato. Soil Biology and Biochemistry 34: 467–476. DOI: https://doi.org/10.1016/S0038-0717(01)00205-X

Cucu M.A., Gilardi G., Pugliese M., Matic S., Gisi U., Gullino M.L., Garibaldi A. 2019. Influence of different biological control agents and compost on total, and nitrification-driven microbial communities at rhizosphere and soil level in a lettuce – *Fusarium oxysporum* f. sp. *lactucae* pathosystem. Journal of Applied Microbiology 26: 905–918. DOI: 10.1111/jam.14153

Cucu M.A., Gilardi G., Pugliese M., Ferrocino I., Gullino M.L. 2020. Effects of biocontrol agents and compost against the *Phytophthora capsici* of zucchini and their impact on the rhizosphere microbiota. Applied Soil Ecology 154: 103659. DOI: https://doi.org/10.1016/j.apsoil.2020.103659

Daneel M., Engelbrecht E., Fourie H., Ahuja P. 2018. The host status of Brassicaceae to Meloidogyne and their effects as cover and biofumigant crops on root-knot nematode populations associated with potato and tomato under South African field conditions. Crop Protection 110: 198–206. DOI: https://doi.org/10.1016/j.cropro.2017.09.001

Deberdt P., Davezies I., Coranson-Beaudu R., Jestin A. 2018. Efficacy of leaf oil from *Pimenta racemosa* var. *racemosa* in controlling bacterial wilt of tomato. Plant Disease 102: 124–131. DOI: https://doi.org/10.1094/PDIS-04-17-0593-RE

Dhima K.V., Vasilakoglou I., Gatsis T., Panou-Philotheou E., Eleftherohorinos I. 2009. Effects of aromatic plants incorporated as green manure on weed and maize development. Field Crops Results 110: 235–241. DOI: https://doi.org/10.1016/j.fcr.2008.09.005

Diab H.G., Hu S., Benson D.M. 2003. Suppression of *Rhizoctonia solani* on impatiens by enhanced microbial activity in composed swine waste-amended potting mixes. Phytopathology 93: 1115–1123. DOI: 10.1094/PHYTO.2003.93.9.1115

Djian-Caporalino C., Mateille T., Bailly-Bechet M. Marteu N., Fazari A., Bautheac P., Raptopoulo A., Van Duong L., Tavoillot J., Martiny P., Goillon C., Castagnone-Sereno P. 2019. Evaluating sorghums as green manure against root-knot nematodes. Crop Protection 122: 142–150. DOI: https://doi.org/10.1016/j.cropro.2019.05.002

Djiwanti S.R., Supriadi, Wiratno 2019. Effectiveness of some clove and citronella oil based-pesticide formulas against root-knot nematode on ginger. IOP Conference Series: Earth and Environmental Science 250: 012090. DOI: 10.1088/1755-1315/250/1/012090

Echeverrigaray S., Zacaria J., Beltrao R. 2010. Nematicidal activity of monoterpenoids against the root-knot nematode *Meloidogyne incognita*. Phytopathology 100: 199–203. DOI: 10.1094/PHYTO-100-2-0199

El-Baha A., El-Sherbiny A., Salme M., Sharrawy N., Mohamed N. 2017. Toxicity of essential oils extracted from *Corymbia citriodora* and *Eucalyptus camaldulensis* leaves against *Meloidogyne incognita* under laboratory conditions. Pakistan Journal of Nematology 35: 93–104. DOI: http://dx.doi.org/10.18681/pjn.v35.i01.p93-104

El-Gizawy K.K.H., Halawa S.M., Mehany A.L. 2018. Effect of essential oils of clove and dill applied as an insecticidal contact and fumigant to control some stored product. Arab Journal of Nuclear Sciences and Application 51: 81–88. DOI: 10.21608/AJNSA.2018.12394

Eljazi J.S., Zarroug Y., Aouini J., Salem N., Boushih E., Jallouli S., Médiouni Ben J.J., Limam F. 2020. Insecticidal activity of *Artemisia herba-alba* and effects on wheat flour quality in storage. Journal of Plant Diseases and Protection 127: 323–333. DOI: https://doi.org/10.1007/s41348-020-00322-0

Eloh K., Kpegba K., Sasanelli N., Koumaglo H.K., Caboni P. 2020. Nematicidal activity of some essential plant oils from tropical West Africa. International Journal of Pest Management 66: 131–141. DOI: https://doi.org/10.1080/09670874.2019.1576950

Fahey J.W., Zalcmann A.T., Talalay P. 2001. The chemical diversity and distribution of glucosinolates and isothiocyanates among plants. Phytochemistry 56: 5–51. DOI: https://doi.org/10.1016/S0031-9422(00)00316-2

Galletti S., Sala E., Leoni O., Burzi P.L., Cerato C. 2008. *Trichoderma* spp. tolerance to *Brassica carinata* seed meal for a combined use in biofumigation. Biological Control 45: 319–327. DOI: https://doi.org/10.1016/j.biocontrol.2008.01.014

Gimsing A., Kirkegaard J. 2009. Glucosinolates and biofumigation: fate of glucosinolates and their hydrolysis products in soil. Phytochemistry Reviews 8: 299–310. DOI: https://doi.org/10.1007/s11101-008-9105-5

Goud J.C., Termorshuizen A.J., Blok W.J., van Bruggen A.H.C. 2004. Long-term effect of biological soil disinfestation on Verticillium wilt. Plant Disease 88: 688–694. DOI: 10.1094/PDIS.2004.88.7.688

Haidar M.A., Sidahmed M.M. 2006. Elemental sulphur and chicken manure for the control of branched broomrape (*Orobanche ramosa*). Plant Protection 25: 47–51. DOI: 10.1016/j.cropro.2005.03.022

Hoitink H.A.J., Boehm M.J. 1999. Biocontrol within the context of soil microbial communities: a soil-dependent phenomenon. Annual Review of Phytopathology 37: 427–446. DOI: https://doi.org/10.1146/annurev.phyto.37.1.427

Hoitink H.A.J., Stone A.G., Han D.Y. 1997. Suppression of plant disease by composts. HortScience 32: 184–187. DOI: https://doi.org/10.21273/HORTSCI.32.2.184

Hollingsworth R.G. 2005. Limonene. A citrus extract, for control of mealybugs and scale insects. Journal of Economic Entomolgy 98: 772–779. DOI: https://doi.org/10.1603/0022-0493-98.3.772

Huang Q., Lakshman D.K. 2010. Effect of clove oil on plant pathogenic bacteria and bacterial wilt of tomato and geranium. Journal of Plant Pathology 92: 701–707. DOI: https://www.jstor.org/stable/41998860

Ibrahim S.K., Traboulsi A.F., El-Haj S. 2006. Effect of essential oils and plant extracts on hatching, migration and mortality of *Meloidogyne incognita*. Phytopathologia Mediterranea 45: 238–246.

Irshad M., Aziz S., Ahmed M.N., Asghar G., Akram M., Shahid M. 2018. Comparisons of chemical and biological studies of essential oils of stem, leaves and seeds of *Zanthoxylum alatum* Roxb growing wild in the state of Azad Jammu and Kashmir, Pakistan. Records of Natural Products 12: 638. DOI: http://doi.org/10.25135/rnp.56.17.11.073

Ji P., Momol M.T., Olson S.M., Pradhanang P.M., Jones J.B. 2005. Evaluation of thymol as biofumigant for control of bacterial wilt of tomato under field conditions. Plant Disease 89: 497–500. DOI: https://doi.org/10.1094/PD-89-0497

Jin X., Wang J., Li D., Wu F., Zhou X. 2019 Rotations with indian mustard and wild rocket suppressed cucumber Fusarium wilt disease and changed rhizosphere bacterial communities. Microorganisms 7: 57. DOI: https://doi.org/10.3390/microorganisms7020057

Kadoglidou K., Chalkos D., Karamanoli K., Eleftherohorinos I., Constantinidou H.I., Vokou D. 2014. Aromatic plants as soil amendments: effects of spearmint and sage on soil properties, growth and physiology of tomato seedlings. Scientia Horticulturae 179: 25–35. DOI: https://doi.org/10.1016/j.scienta.2014.09.009

Kadoglidou K., Lagopodi A., Karamanoli K., Vokou D., Bardas G., Menexes G., Constantinidou H.I., Constantinidou H.I. 2011. Inhibitory and stimulatory effects of essential oils and individual monoterpenoids on growth and sporulation of four soil-borne fungal isolates of *Aspergillus terreus, Fusarium oxysporum, Penicillium expansum* and *Verticillium dahliae*. European Journal of Plant Pathology 130: 297–309. DOI: https://doi.org/10.1007/s10658-011-9754-x

Kadoglidou K., Chatzopoulou P., Maloupa E., Kalaitzidis A., Ghoghoberidze S., Katsantonis D. 2020. Mentha and oregano soil amendment induces enhancement of tomato tolerance against soilborne diseases, yield and quality. Agronomy 10: 406. DOI: https://doi.org/10.3390/agronomy10030406

Kaur S., Singh H.P., Batish D.R., Kohli R.K. 2011. Chemical characterization and allelopathich potential of volatile oil of *Ecualyptus tereticornis* against *Amaranthus viridis*. Journal of Plant Interactions 6: 297–302. DOI: https://doi.org/10.1080/17429145.2010.539709

Khater H.F. 2012. Prospects of botanical biopesticides in insect pest anagement. Pharmacologia 3: 641–656. DOI: http://dx.doi.org/10.5567/pharmacologia.2012.641.656

Kirkegaard J. 2009. Biofumigation for plant disease control – from the fundamentals to the farming system. p. 172–195. In: "Disease Control in Crops: Biological and Environmentally Friendly Approaches" (D. Wlaters, ed.). Wiley-Blackwell, Oxford. DOI: https://doi.org/10.1002/9781444312157.ch9

Kirkegaard J.A., Sarwar M. 1998. Biofumigation potential of Brassicas I- Variation in glucosinolate profiles of diverse field-grown Brassicas. Plant and Soil 201: 71–89. DOI: https://doi.org/10.1023/A:1004364713152

Klose S., Acosta-Martínez V., Ajwa H.A. 2006. Microbial community composition and enzyme activities in a sandy loam soil after fumigation with methyl bromide or alternative biocides. Soil Biology and Biochemistry 38: 1243–1254. DOI: https://doi.org/10.1016/j.soilbio.2005.09.025

Köhl J., Kolnaar R., Ravensberg W. 2019. Mode of action of microbial biological control agents against plant diseases: relevance beyond efficacy. Fronties in Plant Science 10: 845. DOI: https://doi.org/10.3389/fpls.2019.00845

Koiou K., Vasilakoglou I., Dhima K. 2020. Herbicidal potential of lavender (*Lavandula angustifolia* Mill.) essential oil components on bristly foxtail (*Setaria verticillata* (L.) P. Beauv.): comparison with carvacrol, carvone, thymol and eugenol. Archives of Biological Sciences 72: 223–231. DOI: https://doi.org/10.2298/ABS200106016K

Kour D., Rana K.L., Yadav A.N., Dhaliwal H.S., Saxena A.K. 2020. Microbial biofertilizers: bioresources and eco-friendly technologies for agricultural and environmental sustainability. Biocatalysis and Agricultural Biotechnology 23: 101487. DOI: https://doi.org/10.1016/j.bcab.2019.101487

Lagrouh F., Dakka N., Bakri Y. 2017. The antifungal activity of Moroccan plants and the mechanism of action of secondary metabolites from plants. Journal of Mycologie Médicale 27: 303–311. DOI: https://doi.org/10.1016/j.mycmed.2017.04.008

Lazarovits G., Conn K.L., Abbasi P.A., Tenuta M. 2005. Understanding the mode of action of organic soil amendments provides the way for improved management of soil borne plant pathogens. Acta Horticulturae 689: 215–224. DOI: 10.17660/ActaHortic.2005.698.29

Lei J., Leser M., Enan E. 2010. Nematicidal activity of two monoterpenoids and SER-2 tyramine receptor of *Caenorhabditis elegans*. Biochemical Pharmacology 79: 1062–1071. DOI: 10.1016/j.bcp.2009.11.002

Lewis J.A., Papavizas G.C. 1991. Biocontrol of cotton damping-off caused by *Rhizoctonia solani* in the field with formulations of *Trichoderma* spp. and *Gliocladium virens*. Crop Protection 10: 396–402. DOI: https://doi.org/10.1016/S0261-2194(06)80031-1

Makarian H., Poozesh V., Asghari H.R., Nazari M. 2016. Interaction effects of arbuscular mycorrhiza fungi and soil applied herbicides on plant growth. Communications in Soil Science and Plant Analysis 47: 619–629. DOI: https://doi.org/10.1080/00103624.2016.1146744

Markakis E.A., Fountoulakis M.S., Daskalakis G.C, Kokkinis M., Ligoxigakis E.K. 2016. The suppressive effect of compost amendments on *Fusarium oxysporum* f.sp. *radicis-cucumerinum* in cucumber and *Verticillium dahliae* in eggplant. Crop Protection 79: 70–79. DOI: https://doi.org/10.1016/j.cropro.2015.10.015

Matthiessen J.N., Kirkegaard J.A. 2006. Biofumigation and enhanced biodegradation: opportunity and challenge in soilborne pest and disease management. Critical Reviews in Plant Sciences 25: 235–265. DOI: https://doi.org/10.1080/07352680600611543

Mayo-Prieto S., Rodríguez-González A., Lorenzana A., Gutiérrez S., Casquero P.A. 2020. Influence of substrates in the development of bean and in pathogenicity of *Rhizoctonia solani* JG Kühn. Agronomy 10: 707. DOI: https://doi.org/10.3390/agronomy10050707

Mazzola M. 2004. Assessment and management of soil microbial community structure for disease suppression. Annual Review of Phytopathology 42: 35–59. DOI: 10.1146/annurev.phyto.42.040803.140408

Momma N., 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: 247–252. DOI: https://doi.org/10.1007/s10327-006-0274-z

Morales-Rodríguez C., Vettraino A.M., Vannini A. 2016. Efficacy of biofumigation with *Brassica carinata* commercial pellets (BioFence) to control vegetative and reproductive structures of *Phytophthora cinnamomi*. Plant Disease 100: 324–330. DOI: https://doi.org/10.1094/PDIS-03-15-0245-RE

Motisi N., Poggi S., Filipe J.A.N., Lucas P., Doré T., Montfort F., Gilligan C.A., Bailey D.J. 2013. Epidemiological analysis of the effects of biofumigation for biological control of root rot in sugar beet. Plant Pathology 62: 69–78. DOI: https://doi.org/10.1111/j.1365-3059.2012.02618.x

Moutassem D., Belabid L., Bellik Y., Ziouche S., Baali F. 2019. Efficacy of essential oils of various aromatic plants in the biocontrol of Fusarium wilt and inducing systemic resistance in chickpea seedlings. Plant Protection Science 55: 202–217. DOI: https://doi.org/10.17221/134/2018-PPS

Nazzaro F., Fratianni F., Coppola R., Feo V.D. 2017. Essential oils and antifungal activity. Pharmaceuticals 10: 86. DOI: 10.3390/ph10040086

Nerio l.S., Olivero V.J., Stashenko E.E. 2009. Repellent activity of essential oils from seven aromatic plants grown in Colombia against *Sitophilus zeamais* Motschulsky (Coleoptera). Journal of Stored Product Research 45: 212–214. DOI: https://doi.org/10.1016/j.jspr.2009.01.002

Ng L.C., Ismail W.A., Jusoh M. 2017. *In vitro* biocontrol potential of agro-waste compost to suppress *Fusarium oxysporum*, the causal pathogen of vascular wilt disease of roselle. Plant Pathology Journal 16: 12–18. DOI: 10.3923/ppj.2017.12.18

Ntougias S., Papadopoulou K.K., Zervakis G.I., Kavroulakis N., Ehaliotis C. 2008. Suppression of soilborne pathogens of tomato by composts derived from agro-industrial wastes abundant in Mediterranean regions. Biology and Fertility of Soils 44: 1081–1090.

Ochiai N., Powelson M.L., Dick R.P., Crowe F.J. 2007. Effects of green manure type and amendment rate on Verticillium wilt severity of Russet Burbank potato. Plant Disease 91: 400–406. DOI: https://doi.org/10.1094/PDIS-91-4-0400

Oka Y., Nacar S., Putievsky E., Ravid U., Yaniv Z., Spiegel Y. 2000. Nematicidal activity of EOs and their components against the root-knot nematode. Phytopathology 90: 710–715. DOI: https://doi.org/10.1094/PHYTO.2000.90.7.710

Okazaki H., Nose K. 1986. Acetic acid and n-butyric acid as causal agents of fungicidal activity of glucose amended flooded soil. Japanase Journal of Phytopathology 52: 384–393. DOI: https://doi.org/10.3186/jjphytopath.52.384

Okwute S.K. 2012. Plants as potential sources of pesticidal agents: a review. p 207–232. In: “Pesticides – Advances in Chemical and Botanical Pesticides” (R.P. Soundararajan, ed.). IntechOpen Book Series, London, United Kingdom.

Oliveira R.D.L., Dhingra O.D., Lima A.O., Jham J.N., Berhow M.A., Holloway R.K., Vaughn S.F. 2011. Glucosinolate content and nematicidal activity of Brazilian wild mustard tissues against *Meloidogyne incognita* in tomato. Plant Soil 341: 155–164. DOI: https://doi.org/10.1007/s11104-010-0631-8

Ozdemir E., Gozel U. 2018. Nematicidal activities of essential oils against *Meloidogyne incognita* on tomato plant. Fresenius Environmental Bulletin 27: 4511–4517.

Ozores-Hampton M., Stansly P.A., McSorley R., Obreza T.A. 2005. Effects of long-term organic amendments and soil solarization on pepper and watermelon growth, yield, and soil fertility. HortScience 40: 80–84. DOI: https://doi.org/10.21273/HORTSCI.40.1.80

Panth M., Samuel C.H., Baysal-Gurel F. 2020. Methods for management of soilborne diseases in crop production. Agriculture MDPI 10: 1–21. DOI: https://doi.org/10.3390/agriculture10010016

Paret M.L., Cabos R., Kratky B.A., Alvarez A.M. 2010. Effect of plant essential oils on *Ralstonia solanacearum* race 4 and bacterial wilt of edible ginger. Plant Disease 94: 521–527. DOI: 10.1094/PDIS-94-5-0521

Perczak A., Gwiazdowska D., Marchwińska K., Juś K., Gwiazdowski R., Waśkiewicz A. 2019. Antifungal activity of selected essential oils against *Fusarium culmorum* and *F. graminearum* and their secondary metabolites in wheat seeds. Archives of Microbiology 201: 1085–1097. DOI: 10.1007/s00203-019-01673-5

Pontes N.C., Yamada J.K., Fujinawa M.F., Dhingra O.D., de Oliveira J.R. 2019. Soil fumigation with mustard essential oil to control bacterial wilt in tomato. European Journal of Plant Pathology 155: 435–444. DOI: https://doi.org/10.1007/s10658-019-01777-0

Pradhanang P.M., Momol M.T., Olson S.M., Jones J.B. 2003. Effects of plant essential oils on *Ralstonia solanacearum* population density and bacterial wilt incidence in tomato. Plant Disease 87: 423–427. DOI: https://doi.org/10.1094/PDIS.2003.87.4.423

Pugliese M., Liu B.P., Gullino M.L., Garibaldi A. 2011. Microbial enrichment of compost with biological control agents to enhance suppressiveness to four soil-borne diseases in greenhouse. Journal of Plant Diseases and Protection 118: 45–50. DOI: https://doi.org/10.1007/BF03356380

Pugliese M., Gilardi G., Garibaldi A., Gullino M.L. 2015. Organic amendments and soil suppressiveness: results with vegetable and ornamental crops. p. 495–509. In: “Organic Amendments and Soil Suppressiveness” (M. Meghvansi, A. Varma, eds.). Plant Disease Management. Springer, Cham, Switzerland. DOI: https://doi.org/10.1007/978-3-319-23075-7

Ros C., Sánchez F., Martínez V., Lacasa C.M., Hernández A., Torres J., Guerrero M.M., Lacasa A. 2016. El cultivo de brásicas para biosolarización reduce las poblaciones de *Meloidogyne incognita* en los invernaderos de pimiento del Sudeste de España. Información Técnica Económica Agraria 112 (2): 109–126. DOI: https://doi.org/10.12706/itea.2016.008 (in Spanish, with English summary)

Selim E.M.I., Ammar M.M., Amer G.A., Awad H.M. 2020. Effect of some plant extracts, plant oils and *Trichoderma* spp. on tomato Fusarium wilt disease. Menoufia Journal of Plant Protection 5: 155–167.

Singh H.P., Batish D.R., Kaur S., Arora K., Kohli R.K. 2006. Alpha-pinene inhibits growth and induces oxidative stress in roots. Annals of Botany 98: 1261–1269. DOI: https://doi.org/10.1093/aob/mcl213

Smith B.J., Kirkegaard J. 2002. *In vitro* inhibition of soil microorganisms by 2-phenylethyl isothiocyanate. Plant Pathology 51: 585–593. DOI: https://doi.org/10.1046/j.1365-3059.2002.00744.x

Soylu S., Yigitbas H., Soylu E.M., Kurt S. 2007. Antifungal effects of essential oils from oregano and fennel on *Sclerotinia sclerotiorum*. Journal of Applied Microbiology 103: 1021–1030. DOI: https://doi.org/10.1111/j.1365-2672.2007.03310.x

Stella M., Theeba M., Illani Z.I. 2019. Organic fertilizer amended with immobilized bacterial cells for extended shelf-life. Biocatalysis and Agricultural Biotechnology 20: 101248. DOI: https://doi.org/10.1016/j.bcab.2019.101248

Sultana V., Ara J., Ehteshamul-Haque S. 2008. Suppression of root rotting fungi and root knot nematode of chili by seaweed and *Pseudomonas aeruginosa*. Journal of Phytopathology 156: 390–395. DOI: https://doi.org/10.1111/j.1439-0434.2007.01369.x

Thomas W.B. 1996. Methyl bromide: effective pest management tool and environmental threat. Journal of Nematology 28: 586–89.

Tirry N., Kouchou A., Laghmari G., Lemjereb M., Hnadi H., Amranim K., Bahafid W., El Ghachtouli N. 2021. Improved salinity tolerance of *Medicago sativa* and soil enzyme activities by PGPR. Biocatalysis and Agricultural Biotechnology 31: 101914. DOI: https://doi.org/10.1016/j.bcab.2021.101914

Trillas M.I., Casanova E., Cotxarrera I., Ordovas J., Borrero C., Aviles M. 2006. Compost from agricultural waste and the *Trichoderma asperellum* strain T34 suppress *Rhizoctonia solani* in cucumber seedlings. Biological Control 39: 32–38. DOI: https://doi.org/10.1016/j.biocontrol.2006.05.007

Vasilakoglou I., Dhima I., Wogiatzi E., Eleftherohorinos I., Lithourgidis A. 2007. Herbicidal potential of essential oils of oregano or marjoram (*Origanum* spp.) and basil (*Ocimum basilicum*) on *Echinochloa crus-galli* (L.) P. Beauv. and *Chenopodium album* L. weeds. Allelopathy Journal 20: 297–306.

Waisen P., Cheng Z., Sipes B.S., DeFrank J., Wang H. 2020. Effects of biofumigant crop termination methods on suppression of plant-parasitic nematodes. Applied Soil Ecology 154: 103595. DOI: https://doi.org/10.1016/j.apsoil.2020.103595

Yakhlef G., Hambaba L., Pinto D.C.G.A., Silva A.F.S. 2020. Chemical composition and insecticidal, repellent and antifungal activities of essential oil of *Mentha rotundifolia* (L.) from Algeria. Industrial Crops and Products 158: 112988. DOI: https://doi.org/10.1016/j.indcrop.2020.112988

Yener I. 2020. Determination of antioxidant, cytotoxic, anticholinesterase, antiurease, antityrosinase, and antielastase activities and aroma, essential oil, fatty acid, phenolic, and terpenoid-phytosterol contents of *Salvia poculata*. Industrial Crops and Products 155: 112712. DOI: https://doi.org/10.1016/j.indcrop.2020.112712

Zasada I.A., Ferris H. 2004. Nematode suppression with brassicaceous amendments: Application based upon glucosinolate profiles. Soil Biology and Biochemistry 36: 1017–1024.

Zhao F., Zhang Y., Dong W., Zhang Y., Zhang Y., Sun Z., Yang L. 2019. Vermicompost can suppress *Fusarium oxysporum* f. sp. *lycopersici* via generation of beneficial bacteria in a long-term tomato monoculture soil. Plant Soil 440: 491–505. DOI: https://doi.org/10.1007/s11104-019-04104-y

Zhou X.G., Everts K.L. 2004. Suppression of Fusarium wilt of watermelon by soil amendment with hairy vetch. Plant Disease 88: 1357–1365. DOI: https://doi.org/10.1094/PDIS.2004.88.12.1357

Ziedan E.H., Saad M.M., El-Naggar M.A., Hemida K.A., El Samman M.G.A., Mostafa H.M. 2020. Efficacy of compatibility between endophytic biocontrol agents and abiotic agents as fungicides alternatives for controlling root rot of grapevine. Acta Scientific Agriculture 4 (5): 10–17.