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 $\cdot$ 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*<br>*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 | Fusarium wilt | *Fusarium oxysporum* f. sp. *radicis cucumerinum* | cucumber | Markakis *et al*. (2016) |
| Tomato pulp, sawdust, chipping wood | 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:<br>1. ANT's (V – CV)<br>2. ANT's ( M – CM)<br>3. ANT's (B – CB)<br>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)<br>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.,<br>*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 $mg \cdot l^{-1}$, 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<br>palmarosa<br>lemongrass | tomato | Pradhanang *et al*. (2003) |
| | thymol<br>palmarosa | tomato | Ji *et al*. (2005) |
| | clove | tomato | Huang and Lakshman (2010) |
| | clove | 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<br>mint | tomato | Selim *et al*. (2020) |
| | oregano<br>spearmint | tomato | Kadoglidou *et al*. (2020) |
| Fusarium wilt (*F. oxysporum* f. sp. *ciceris*) | thyme<br>lemongrass<br>laurell | chickpea | Moutassem *et al*. (2019) |
| Nematode diseases | | | |
| Root-knot nematode (*Meloidogyne incognita*) | *Eruca sativa* | tomato | Aissani *et al*. (2015) |
| | *Artemisa absinthium*<br>*Lavandula officinalis*<br>*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 $\alpha$-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.

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