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Review

Management of soil-borne diseases of organic vegetables

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Abstract: With the rising awareness of the adverse effects of chemical pesticides, people are looking for organically grown vegetables. Consumers are increasingly choosing organic foods due to the perception that they are healthier than those conventionally grown. Vegetable crops are vulnerable to a range of pathogenic organisms that reduce yield by killing the plant or damaging the product, thus making it unmarketable. Soil-borne diseases are among the major factors contributing to low yields of organic produce. Apart from chemical pesticides there are several methods that can be used to protect crops from soil-borne pathogens. These include the introduction of biocontrol agents against soil-borne plant pathogens, plants with therapeutic effects and organic soil amendments that stimulate antagonistic activities of microorganisms to soil-borne diseases. The decomposition of organic matter in soil also results in the accumulation of specific compounds that may be antifungal or nematicidal. With the growing interest in organic vegetables, it is necessary to find non chemical means of plant disease control. This review describes the impact of soil-borne diseases on organic vegetables and methods used for their control.

Key words: control, biological antagonists, organic manure, organic vegetables, seaweeds, soil-borne diseases

Introduction

Rising awareness of the adverse effects of chemical pesticides and an increasing demand for organic fruits and vegetables have encouraged growers to transit to sustainable and organic production systems (Klonsky 2004). Such ecologically sound systems have the potential to address a number of ongoing issues in mainstream agriculture, namely pollution due to synthetic chemical fertilizers and pesticides, production losses due to pest and disease pressure, soil degradation, loss of soil fertility and productivity (Engindeniz and Cosar 2013). Organic farming pursues a course of promoting self-regulation and resistance which plants and animals possess naturally. Especially in poorer countries, it can contribute to purposeful socio-economic and ecologically sustainable development (Willer and Yussefi 2004). During the last decade, many countries of the European Union, the United States, and also countries in Latin America, Africa, Asia and Oceania have experienced a significant increase in certified organic farms. Almost 23 mln ha are managed organically worldwide. According to the International Trade Center, annual sales grew from US $17.5 billion in 2000 to US $21 billion in 2001. Growth rates for 2003–2005 are estimated to be from 5–15%. About 90 developing countries (of which about 15 are less developed) export certified organic products, namely tropical and off-season commodities (Willer and Yussefi 2004).

Soil biology is directly linked to agricultural sustainability as it is the driving force behind decomposition processes that break down complex organic molecules and substances and convert them into plant available forms (Friedel *et al*. 2001). Large, stable, and active soil microbial communities are important for sustaining the productivity of soils under sustainable and organic farming systems. To develop such systems growers adopt strategies such as crop rotation, cover cropping, and application of organic amendments (manures and composts) that significantly increase soil organic matter (SOM) and improve soil biology and quality (Buyer *et al*. 2010).

The significance of organic vegetables

According to the USDA (United States Department of Agriculture) National Organic Standards Board (NOSB), organic agriculture is defined as “an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. It is based on the minimal use of off-farm inputs and on

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management practices that restore, maintain or enhance ecological harmony. The primary goal of organic agriculture is to optimize the health and productivity of interdependent communities of soil life, plants, animals and people".

Consumers are becoming increasingly concerned about how, where and when foods are produced. The demand for organic products is also increasing as people become aware of the benefits of organic produce. This has led to an increased consumer interest in organically grown vegetables including those produced in greenhouses. One of the core philosophies of organic production systems is the development of healthy and productive soil that provides essential nutrients for plant growth, supports diverse and active soil biotic communities and balances the entire farm ecosystem. There is a growing demand for organic products since more and more consumers feel that they are healthier than those conventionally grown (Yiridoe *et al.* 2007). Globally there are about 37,232,127 ha of organically managed land with Australia accounting for 32.2% (Paull 2011). It has been reported that overall organic produce contains 5.7% more micronutrients than comparable conventionally grown produce (Hunter *et al.* 2011). The annual global sale of organic food is estimated to be about US $60 billion (Paull 2011). Organic food consumption is part of a way of life and is associated with a strong interest in nature, society and the environment (Schifferstein and Ophuis 1998). However, consumers are sometimes confused and the term 'organic' is interpreted in a variety of ways. It is often associated with terms like 'ecological', 'green', 'natural' and 'sustainable' (Aarset *et al.* 2004).

Soil-borne diseases

Soil-borne diseases are one of the major factors contributing to low yields of organic products. Vegetable crops are vulnerable to a range of pathogenic organisms that reduce yield by damaging whole plants or valued products and make them unmarketable. Plant diseases are responsible for as much as 26% of yield loss in global agriculture and sometimes there may be complete crop failure (Khan *et al.* 2009). Although the development of plant diseases is a regular part of an ecosystem and crop production, it becomes a concern when the diseases assume an epidemic form causing enormous crop losses (Morsy *et al.* 2009). Some of the most important soil-borne diseases are caused by pathogens that are 'soil inhabitants', have broad host ranges that include weeds, and produce long-lived survival structures. Important soil-borne pathogens include fungi, fungi-like organisms, bacteria as well as viruses and plant parasitic nematodes (Baysal-Gurel *et al.* 2012). Fungal pathogens, including species of *Fusarium*, *Rhizoctonia*, *Verticillium*, *Sclerotinia* and *Macrophomina phaseolina*, cause the loss of billions of dollars each year. Many soil-borne fungi persist in the soil for long periods by producing resistant survival structures such as chlamydospores, oospores and sclerotia (Baysal-Gurel *et al.* 2012). Important soil-borne bacterial pathogens include *Ralstonia*, *Pectobacterium*, *Agrobacterium* and *Streptomyces* (Baysal-Gurel *et al.* 2012). Pathogens in the *Pseudomonas* and *Xanthomonas* groups usually persist in the soil for only a short time. Soil-borne viruses that infect vegetables are few in number and generally survive only in the living tissues of the host plant or in insects, the nematode or fungal vectors that transmit them (Baysal-Gurel *et al.* 2012).

Root-knot nematodes (*Meloidogyne* spp.) are serious and economically the most important pest of many cultivated crops around the world (Youssef and Lashein 2013). Root-knot nematodes are sedentary endoparasites and are among the most damaging agricultural pests attacking a wide range of crops. They particularly damage vegetables in tropical and subtropical countries (Sikora and Fernandez 2005; Adam *et al.* 2014) and cause losses of up to 80% in heavily infested fields. Economically root-knot nematodes constitute the most important phytonematode. Collectively, they parasitize more than 2,000 plant species with vegetables and horticultural crops being highly susceptible (Adam *et al.* 2014). Losses caused by plant parasitic nematodes are estimated to be about US $100 billion annually (Saifullah *et al.* 2007).

Fusarium solani and *R. solani* are the most important soil-borne fungal pathogens, which develop in both cultured and non-cultured soils, causing damping-off and root rot diseases in a wide range of vegetable and crop plants including tomato (Szczechura *et al.* 2013). The incidence of damping-off was increased from 19 to 90% with increasing inoculum levels of *Rhizoctonia solani*, while the incidence of root rots caused 10 to 80% losses in different vegetables. *Rhizoctonia solani*, an important destructive soil-borne pathogen has detrimental effects on agricultural and horticultural crops by pre-emergence and post-emergence damping-off, root rot, and stem canker. Its host plants include alfalfa, peanut, soybean, lima bean, cucumber, papaya, eggplant, corn and many more (Keijer *et al.* 1997).

Macrophomina phaseolina, which causes charcoal rot, is cosmopolitan in distribution and is a potential threat to crop production in arid regions (Ijaz *et al.* 2013). It is a soil inhabiting fungus, an important root pathogen and causes dry root rot/stem canker, stalk rot or charcoal rot in over 500 plant species (Khan 2007). The wide host range of *M. phaseolina* suggests that it is a non-host-specific fungus. Charcoal rot is of great economic importance in arid areas of the world and has been reported to be the major limiting factor for sunflower production (Khan 2007; Ijaz *et al.* 2013). Damping-off and root rot caused by the *Pythium* are considered to be among the most devastating diseases of greenhouse-grown crops. This pathogen affects nearly every crop grown in every part of the world. The main causal agent of the damping-off and root rot is *Pythium aphanidermatum*. Some *Pythium* species are among the most destructive plant pathogens (Agrios 2005). The majority of *Pythium* species are capable of parasitizing seeds, seedlings, and older stages of a wide range of plants causing damping-off disease. However, the greatest damage is done to the seeds and the roots of seedlings either before or after emergence (Agrios 2005).

Phytophthora is a soil-borne fungus that can attack the roots, crown and fruits of many crop varieties (Fig. 1). The disease is more active under wet conditions and is spread by contamination of soil. *Phytophthora capsici* at-

Fig. 1. Okra field infected with *Fusarium* and *Phytophthora*

tacks a wide variety of vegetables, fruits, grains and floral crops. It may remain viable for 10 years or more in soil (Baysal-Gurel *et al.* 2012). It is difficult to estimate yield losses due to *Phytophthora* diseases since the same species may cause a number of other diseases, in different environmental conditions, particularly rainfall and humidity, can have a dramatic effect on disease incidence and severity (Benson *et al.* 2006). Most *Phytophthora*-related losses can be attributed to *Phytophthora* pod rot (PPR) followed by stem cankers. It is commonly estimated that 10–20% of the world's annual production is lost due to PPR, but estimates vary from average annual losses of 10% up to 30%, with much higher losses in particularly wet locations or during wet years (Erwin and Ribeiro 2006). In Western Samoa, losses of 60–80% due to PPR in wet years were reported by Keane (1992).

Control of soil-borne diseases

Most soil-borne pathogens are difficult to control by conventional strategies such as the use of resistant cultivars and synthetic pesticides (Weller *et al.* 2002). Soil application of fungicides is expensive and deleterious to non-target microflora. Biological control has become a critical component of plant disease management and it is a practical and safe approach in various crops (Patel and Anahosur 2001). Bioprotectants provide a unique opportunity for crop protection, since they grow, proliferate, colonize and protect the newly-formed plant parts to which they were not initially applied. Soil biology is directly linked to agricultural sustainability since it is the driving force behind decomposition processes that break down complex organic molecules and substances and convert them into plant available forms (Friedel *et al.* 2001). A large, stable and active soil microbial community is an underpinning for maintaining the productivity of soils under sustainable and organic farming systems. To develop such systems growers adopt such strategies as crop rotation, cover cropping, application of organic amendments (manures and composts) and biological antagonists (Shafique *et al.* 2015a, b). Along with cover crops, the use of compost and manure is considered to be an integral component of organic production since it provides essential plant nutrients and improves soil quality and structure (Russo and Webber 2007). The elucidation of the effect of such alternative practices on soil-borne pathogens is needed for the design of soil and crop management systems that are also suppressive to soil-borne pathogens and their root diseases. Several books and review articles have been published on this subject including ways to assess and quantify it (Doran *et al.* 1994).

Plant products

Plants with therapeutic effects have received the attention of scientists as an alternate method of disease control which protects the environment from the use of hazardous chemicals. Crop rotation, in general, provides numerous benefits to crop production. Application of botanical toxicants or plant products has been reported to reduce root-knot disease (Al-Askar 2012; Khalil *et al.* 2012). They can help conserve, maintain, or replenish soil resources, including organic matter, nitrogen and other nutrient inputs, as well as physical and chemical properties (Ball *et al.* 2005; Ladygina and Hedlund 2010). Crop rotation has been associated with increased soil fertility, increased soil tilth and aggregate stability, improved soil water management and reduced erosion (Ball *et al.* 2005). For example, crops in the Brassicaceae family which include broccoli, cabbage, cauliflower, turnip, radish, canola, rapeseed and various mustards, produce sulfur compounds that break down to produce isothiocyanates that are toxic to many soil organisms as part of a process referred to as biofumigation (Youssef and Lashein 2013). Use of these plants as rotation, cover, or green manure crops has been observed to reduce soil-borne diseases or populations of fungal pathogens and nematodes and to improve soil characteristics and crop yield (Larkin and Griffin 2007). Further studies have indicated that additional mechanisms, including specific changes in soil microbial communities unrelated to levels of toxic metabolites, are also important in the reduction of soil-borne diseases by *Brassica* crops (Mazzola *et al.* 2004; Larkin and Griffin 2007). Crop rotation is one of the most effective tools for managing pests and maintaining soil fertility. A common approach on vegetable farms is to rotate crops by families. Another strategy is to alternate vegetable crops with field or forage crops such as small grains, alfalfa or clovers. Some growers try to rotate fields so they are in cash crops one year and cover crops the next year. Sweet corn is a good crop to rotate with since it hosts very few insects or diseases that affect other vegetables. For diseases that are soil-borne or over-winter in crop residues, rotating out of susceptible crops is a key in preventing infection, as in the case of Phytophthora blight, early blight, and many other diseases.

It is known that plants and plant products (organic amendments, crop residues, green manures) can dramatically affect soil microbial communities, and are primary drivers of soil microbial dynamics (Hoitink and Boehm 1999; Garbeva *et al.* 2004), and thus may be important components in establishing and maintaining soil suppressiveness. Crop rotations and residue amendments have been shown to have major effects on soil microbial communities and can result in significant reductions in soil-borne diseases (Abawi and Widmer 2000; Bailey and Lazarovits 2003). Green manures of cabbage and cauliflower leaves, chopped pineapple leaves, dry straw of rice, rye or oats and cotton wastes are reported to reduce the incidence of root-knot in the field (Youssef and Lashain 2013).

Organic manures

With the rising popularity of organic farming due to adverse effects of chemicals, the organic fertilizer industry is growing rapidly (Sultana *et al.* 2011b). Organic amendments are generally used for improving crops, increasing agricultural productivity and suppressing soil-borne diseases (Hoitink and Boehm 1999; Stone *et al.* 2003). The quantity of nutrients in manures varies with the type of animal, feed composition, quality and quantity of bedding material, length of storage and storage conditions (Dewes and Hunsche 1998). The application of organic amendments has been proposed as a strategy for the management of diseases caused by soil-borne pathogens. Organic amendments with organic wastes, composts and peats, have been proposed to control diseases caused by soil-borne pathogens. There are many examples of soil-borne pathogens controlled effectively by the application of organic amendments: like *Gaeumannomyces graminis* f. sp. *tritici, M. phaseolina, R. solani*, *Thielaviopsis basicola, Verticillium dahliae*, species of *Fusarium*, *Phytophthora*, *Pythium* and *Sclerotium* (Bonanomi *et al.* 2007). Tuitert *et al.* (1998) reported that un-decomposed and mature composts were suppressive to *R. solani* damping-off, but partially decomposed materials were conducive. Compost extracts are gaining popularity particularly among those who are seeking substitutes to agrochemicals (Bess 2000).

Compost when properly prepared and used can help and promote low-input agricultural systems to become more sustainable and productive (Golabi *et al.* 2003). Matured composts, even without microbial inoculation, are already valuable. However, continuing research shows that options which employ microbial inoculation in compost tend to further improve its productivity. Composted manure thus has a more long-term role in building soil fertility, and has been shown to be more effective in building soil microbial biomass and increasing activity than uncomposted manure (Fließach and Mäder 2000). Similarly, additions of large quantities of organic matter were found to create anaerobic conditions that contributed to the reduction of inoculums of *Fusarium oxysporum* f. sp. *asparagi*, *R. solani* and *V. dahliae* (Blok *et al.* 2000).

Compost extract contains a high population of microbiota, e.g. rhizobacteria, *Trichoderma* and *Pseudomonas* spp., which may enhance growth and yield of crops (Welke 2005). These microbiota produce plant growth hormones and chemical compounds (e.g. siderophores, tannins, phenols) which are antagonistic to various soil pathogens. The use of compost extract is also claimed to increase soil C levels, improve soil structure, nutrient cycling and water holding capacity, and suppress plant diseases (Ghorbani *et al.* 2008). However, to achieve these benefits, several variables have to be considered to produce compost extracts of the desired quality. These include microbial food sources, compost to water ratio, levels of aeration, compost quality, compost age, duration of incubation, and the quality of water used. There is also a need for consistent compost quality which depends on consistency of inputs and methods used to produce compost. Organic matter amendments to soil have been shown to have beneficial effects on soil nutrients, physical condition and biological activity as well as crop viability (Hulugalle *et al.* 1986).

Besides a wide variety of organic matters that have been tested as organic amendments for managing plant pathogens, oil seed cakes decreased the population of soil-borne pathogens (Shafique *et al.* 2015b). Oil seed cakes are by-products obtained after oil extraction from seeds. Oil seed cakes are of two types, edible and non-edible. Non-edible oil seed cakes such as castor cake and neem cake are used as organic nitrogenous fertilizers, due to their NPK content. Some of these oil cakes have been found to increase the nitrogen uptake by the plant and protect the plants from soil nematodes, insects, and parasites (Ramachandran *et al.* 2007). Several antimicrobial by-products (e.g. organic acids, hydrogen sulfide, phenols, tannins and nitrogenous compounds) are released during the decomposition of organic amendments, or synthesized by microorganisms involved in such degradation (Rodríguez-Kábana *et al.* 1995).

Seaweed fertilizers

Application of seaweeds as an organic soil amendment has increased in recent years due to rising awareness of the adverse effects of chemical pesticides (Mazzola 2004; Sultana *et al.* 2011b). The high fiber content of seaweed acts as a soil conditioner and assists moisture retention, while the mineral content is a useful fertilizer and source of trace elements (Mat-Atko 1992). They also contain biocontrol properties and contain many organic compounds and growth regulators such as auxins, gibberellins and precursor of ethylene and betaine which affect plant growth. Seaweed extracts have been reported to increase plant resistance to pests and diseases, plant growth, yield and quality (Mat-Atko 1992). Seaweeds contain elaborate, secondary metabolites that play a significant role in the defense of the host against pathogens and parasites (Ara *et al.* 2005). Seaweed could affect cell metabolism through the induction of the synthesis of antioxidant molecules which could favor plant growth and plant resistance to stress (Zhang and Schmidt 2000). Anti-oxidant enzymes provide a degree of crop protection from free radical oxidants arising from normal metabolism and any number of biotic and abiotic stresses. Wu *et al*. (1997) demonstrated that the betaines present in different extracts decreased nematode infestation. Furthermore, seaweeds suppressed root rotting fungi and the root-knot nematode by producing antimicrobial compounds or synthesis of antioxidant molecules. Seaweeds contain 1-aminocyclopropane-1-carboxylic acid (ACC), which has antimicrobial activity (Nelson and Van Standen 1985). Similarly, polyphenols are well known for their antioxidant activity and are widely distributed in seaweeds (Tariq *et al*. 2011). A red seaweed *Solieria robusta* used as a soil amendment showed better suppression of root rotting fungus *F. solani* than Topsin-M (Sultana *et al.* 2011a). Soil amendment with seaweed was also found to be effective in reducing root-knot infection besides improving plant growth both in field plots and farmers' fields (Baloch *et al.* 2013). Seaweeds were also found effective on eggplant, a plant which is highly susceptible to root-knot nematode under field conditions (Baloch *et al.* 2013). Liquid concentrations of brown algae *Ecklonia maxima* significantly reduced root-knot infestation and increased the growth of tomato plants. It has also been shown that seaweeds occurring on the Karachi, Pakistan coast have nematicidal, fungicidal and antibacterial properties (Ara *et al.* 2005) and soil amendment with seaweeds with or without a biocontrol agent significantly reduced the root-knot nematode (*Meloidogyne javanica*) and root infecting fungi on various crops (Sultana *et al.* 2011a, b).

Biological antagonists

With the rising awareness of the adverse effects of chemical pesticides interest in the introduction of biocontrol microbes into the rhizosphere is increasing. Different mechanisms of biocontrol agents are supposed to contribute to the suppression of soil-borne plant pathogens, parasitism, production of antifungal compounds, competition for nutrients and colonization sites, and induction of systemic resistance in plants against pathogens. Disease suppressive composts containing biological control agents are the major component of the total product. Van Bruggen (1995) found that cellulolytic and hemicellulolytic actinomycetes were present in much higher numbers in organically amended soils than those using chemical fertilizers.

Several antagonistic organisms have been successfully used as biocontrol agents for controlling soil-borne pathogens (Afzal *et al.* 2013; Kowsari *et al.* 2014). In most of the research to date, biocontrol agents are applied singly to combat the growth of pathogens. Although the potential benefits of a single biocontrol agent application has been demonstrated in many studies, but in many cases they showed inconsistent performance because a single biocontrol agent is not likely to be active in all kinds of soil environments and all agricultural ecosystems (Raupach and Kloepper 1998). These have resulted in inadequate colonization, limited tolerance to changes in environmental conditions and fluctuations in the production of antifungal metabolites (Weller *et al.* 2002). Mixtures of biocontrol agents also have the advantage of exercising a broad spectrum activity, in general enhancing the efficacy and reliability of biological control and ensuring greater induction of defense enzymes over individual strains (Latha *et al.* 2009). A highly effective biocontrol strain should be able to both compete and persist in the environment and to colonize and proliferate on plant parts. It should be very inexpensive and maintain good viability without a specialized storage system (Harman 1996).

Soil application of biocontrol agents viz. *Trichoderma viride, T. harzianum,* fluorescent *Pseudomonas* and *Bacillus subtilis* effectively reduced root rot caused by soil-borne pathogens in several crops (Loganathan *et al.* 2010; Shafique *et al.* 2015b). *Trichoderma* spp. are known to produce large quantities of fungi toxic metabolites. The inhibitory effect of *Trichoderma* spp. might be due to direct mycoparasitism in addition to competition for nutrients (Sharon *et al.* 2001; Afzal *et al.* 2013). *Trichoderma* spp. are active mycoparasites that have been considered for biocontrol of foliar and soil-borne diseases as well as plant parasitic soil-borne nematodes (Kowsari *et al.* 2014). *Trichoderma* spp. can provide excellent control against root-knot nematodes such as *T. harzianum* (Sharon *et al.* 2001), and are viewed as strong contenders for development as biocontrol agents. However, differences in the efficacy among isolates, their biocontrol potential and the reproducibility of results under different conditions have impeded their development (Sharon *et al.* 2001). Increasingly, *Trichoderma* spp. are being investigated for their biocontrol potential against root-knot nematodes on a range of crops, such as tomato, okra, mungbean and bell pepper (Meyer *et al.* 2001). Afzal *et al.* (2013) found that endophytic *T. viride* was effective in suppressing the *F. solani, F. oxysporum* and root-knot nematode on okra used alone or with *Pseudomonas aeruginosa* (Fig. 2).

Chaetomium, *Penicillium* and *Trichoderma* species are biological control agents that have the potential to control plant diseases. Naraghi *et al.* (2010) reported successful biological control of tomato verticillium disease by antagonistic effects of *Talaromyces flavus*. Field trials have shown that *Chaetomium* formulated bioproducts have promise as broad spectrum mycofungicides to control many diseases (Soytong *et al.* 2001). Similarly the application of bioproducts from *Chaetomium* can protect and cure *Thielaviopsis* bud rot of *Hyophorbe lagenicaulis* in Thailand (Soytong *et al*. 2001). It is well known that actinomy-

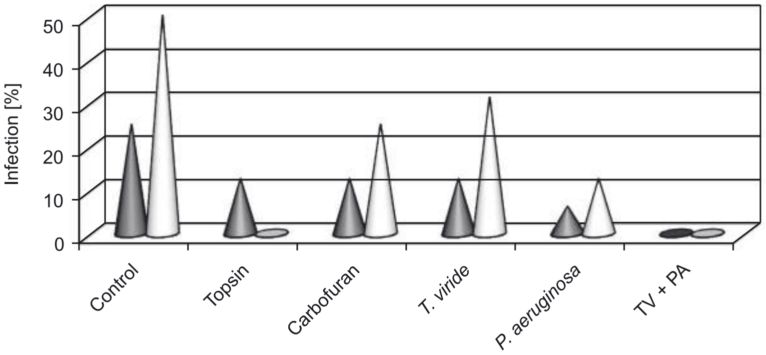

Fig. 2. Effect of endophytic *Trichoderma viride* (TV) and *Pseudomonas aeruginosa* (PA) on infection of *Fusarium solani* (dark bar) and *F. oxysporum* (white bar) on okra roots

cetes produce 70–80% of bioactive secondary metabolites, where approximately 60% of antibiotics developed for agricultural use are isolated from *Streptomyces* spp. (Ilic *et al.* 2007). It has an enormous biosynthetic potential that remains unchallenged, and is without a potential competitor among other microbial groups (Solanki *et al.* 2008). Many reports have pointed out that since streptomycetes are frequently screened for antimicrobial activity, the existence of secondary metabolites with other activities may have been missed (Garcia *et al.* 2000). This microbial wealth from actinomycetes has yet to be investigated thoroughly. Similarly inoculation of soil with *Paecilomyces lilacinus* resulted in considerable reduction of nematode multiplication. The ability of *P. lilacinus* to control nematodes increased when it was integrated with organic matters. It is assumed that the decomposition of organic matter released nematicidal properties and residual organic matter increased fungal activity and persistence (Mani and Anandam 1989). A combined use of *P. lilacinus* with *P. aeruginosa* has been found to be more effective in reducing the infection of root-infecting fungi and root-knot nematode on pumpkin, guar, chili and watermelon (Perveen *et al.* 1998). *Paecilomyces lilacinus,* besides parasitizing eggs of root-knot and cyst nematodes also produced nematicidal metabolites (Jatala *et al.* 1990).

In addition to antagonistic fungi and bacteria the arbuscular mycorrhizal fungi (AMF) have also been used against soil-borne diseases (Berta *et al.* 2005). Vesicular arbuscular endo-mycorrhizas, the most common type of mycorrhizal association, are formed by nearly all cultivated plants whether they are agricultural, horticultural or fruit crops (Pfleger and Linderman 2000). The importance of this type of symbiotic fungal infection for plant mineral nutrition and more generally for plant health (Sood 2003), makes it potentially one of the more useful biological means of assuring plant production with a minimum input of chemicals such as fertilizers or pesticides (Pfleger and Linderman 2000). Vesicular arbuscular mycorrhizae (VAM) enhance plant growth through increased nutrient uptake, stress tolerance and disease resistance (Bouamri *et al.* 2006). There are reports that VAM decrease the severity of disease caused by plant pathogenic fungi (Filion *et al.* 2003). Vesicular arbuscular mycorrhizae can reduce damage from *Rhizoctonia* on several plant species and other plant pathogen combinations (Berta *et al.* 2005), Fusarium crown and root rot and *Phytophthora* disease on tomato (Cordier 1996) and Verticillium wilt of cotton (Liu 1995). Enhanced nutrient status of the plant for VAM citrus, high arginine levels in VAM tobacco that were inhibitory to pathogen chlamydospores and cell thickenings in VAM onion which restricted pathogen penetration (Pfleger and Linderman 2000) were found.

The plant growth promoting rhizobacteria (PGPR) are rhizospheric microbes which produce bioactive substances and promote plant growth and/or protect them against pathogens. Root colonizing bacteria that have a beneficial effect on plants are termed plant growth promoting rhizobacteria and are reported to improve plant growth either through direct stimulation of the plant by producing growth regulators or by suppression of pathogens (Raaijmakers *et al.* 2002). Of the various rhizospheric bacteria, the bacteria belonging to the fluorescent *Pseudomonas* which colonize roots of a wide range of crop plants are reported to be antagonistic to soil-borne plant pathogens (Siddiqui and Ehteshamul-Haque 2001). The production of certain antibiotics (Raaijmakers *et al.* 2002) and siderophores (De Meyer and Hofte 1997) by *P. aeruginosa* has been regarded as one of the mechanisms involved in antagonism. Raajimakers and Weller (1998) reported the role of 2,4-diacetylphloroglucinol, an antifungal metabolite from species of fluorescent *Pseudomonas* in plant root disease suppression.

Induction of systemic resistance by PGPR and antagonistic fungi against diseases, insect and nematode pests

Several possible mechanisms including the production of antifungal metabolites, competition for space and nutrients, mycoparasitism, plant growth promotion and induction of the defense responses in plants have been suggested as mechanisms for their biocontrol activity (Howell 2003). When identifying potential biocontrol agents, antifungal metabolites produced by them are important factors to be taken into account. Many research groups are actively trying to find metabolites produced by biocontrol agents which will suppress particular diseases (Dowling and O'Gara 1994). Certain biochemical changes occurring after the application of biocontrol agents can act as markers for induced systemic resistance. These include accumulation of certain enzymes, such as peroxidase (Govindappa *et al.* 2010). Among the new biological approaches, the stimulation of natural plant defenses is considered to be one of the most promising alternative strategies for crop protection (Walters and Fountaine 2009). This original biological approach does not exert direct effects on the pathogen (Walters and Fountaine 2009) but stimulates natural defenses in plants, leading to a systemic acquired resistance (Goel and Paul 2015). The induction of plant defense mechanisms was associated with the production of elicitors by the plant-host (endogenous elicitor) (Montesano *et al.* 2003). The accumulation of salicylic acid (SA) during systemic acquired resistance is preceded by a transient increase in phenylalanine ammonia-lyase (PAL) activity and inhibition of PAL activity suppresses the systemic acquired resistance (Mandal *et al.* 2009). The systemic activation of the defense mechanisms was accompanied by a systemic acquired resistance to insects, nematodes, fungi, bacteria and viruses (Bakker *et al.* 2013). Salicylic acid is now the focus of intensive research due to its function as an endogenous signal mediating local and systemic plant defense responses against pathogens. It has also been found that SA plays a role during the plant response to abiotic stresses such as drought, chilling, heavy metal toxicity, heat, and osmotic stress. In this sense, SA appears to be an 'effective therapeutic agent' for plants. The discovery of its targets and the understanding of its molecular modes of action in physiological processes could help in the dissection of the complex SA signaling network (Vicente and Plasencia 2011).

Conclusion

Organic farming is gaining worldwide acceptance and is becoming a major tool for sustaining the quality of degraded soils due to the intensive use of synthetic chemicals for increasing crop production. The use of bio-agents, such as biofertilizers or biopesticides is an integral part of organic farming especially in vegetable cultivation. The nature of the organic amendments, the microorganisms present, the properties of the soil, and environmental conditions are key factors that can influence the populations of soil-borne plant pathogens and the crop to be protected. Using organic amendments, antagonistic microorganisms and phytochemicals in controlling soil-borne root infecting fungi offers an alternate strategy to the prevalent use of synthetic pesticides. Mixtures of biocontrol agents have the advantage of exercising a broad spectrum activity, enhancing the efficacy and reliability of biological control and ensuring greater induction of defense enzymes in an individual. However, in many cases the application of more than one biocontrol agent did not yield any added advantage.

Plant growth in organic systems greatly depends on the functions performed by soil microbes particularly in nutrient supply. The build-up of a large and active soil microbial biomass, therefore, is critically important for sustaining the productivity of soils in organic farming systems. More research is needed to identify and characterize locally available amendments and the impact of antagonistic organisms as related to potential soil-borne pathogen control. This review also indicated that a single management approach or practice such as a biological amendment or crop rotation, alone will probably not be effective in establishing disease suppression, but multiple approaches such as combinations of rotations, cover crops, organic and biological amendments, need to be optimized and coordinated together as part of an integrated soil management program. Active management of soil microbial communities for disease suppression through the use of effective crop rotations and biological amendments has much potential, but more research is needed to determine the effects and interactions among microorganisms, the most effective crop and amendment combinations and their practical implementation.

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