Chapter 2
Sustainable Management of Soil-Borne Plant Pathogens

Dina S. S. Ibrahim, Manal Mostafa, Aya A. M. Abdellatif, and Rizwan Ali Ansari

Abstract In an attempt to fulfill the increased food demands of an explosive population, synthetic fertilizer and pesticide-ridden food production have steadily increased, considerably affecting the agroecosystem. Consumers throughout the world have not been informed of the detrimental effects of these chemicals. Many soil-borne pathogens including phytonematodes are aggressively managed in the presence of non-judicious chemical fertilizers. Resultantly, many developed as well as developing countries have embraced organic cultivation efforts and experienced outstanding results. In sustainable management, a wide range of biocontrol microorganisms including fungi, bacteria, and actinomycetes are available for use at a commercial scale without causing any perturbation to the natural biota. Recently, biocontrol and microbial-based biopesticides have provided great promise in soil and plant health improvement. Mechanisms such as antibiosis, hyperparasitism, food and space competition, and induced systemic resistance (ISR) induction are implicated in the reduction of nematode/pathogen populations. Organic matter and beneficial microorganisms improve plant growth and yield performance and also curtail the attack of a wide spectrum of pests and pathogens. However, there are some minor lacunas encountered in the use of these microorganisms at a large scale which require addressing in future studies. Genomics to metagenomics studies are required to obtain amicable solutions for producers.

D. S. S. Ibrahim (✉) · M. Mostafa
Department of Nematodes Diseases, Central Laboratory of Biotechnology, Plant Pathology Research Institute, Agricultural Research Center (ARC), Giza, Egypt
e-mail: Dina.Serag@arc.sci.eg; mickeyocean@yahoo.com; manal.mustafa93@gmail.com

A. A. M. Abdellatif
Central Laboratory of Organic Agriculture, Agricultural Research Center (ARC), Giza, Egypt
e-mail: aya_aloraby90@yahoo.com

R. A. Ansari
Department of Plant Protection, Faculty of Agricultural Sciences, Aligarh Muslim University, Aligarh, India
e-mail: rizwans.ansari@gmail.com

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2.1 Introduction

Plant health and agroecosystem potentiality are dependent on beneficial phytobiomes. Ecosystem services such as storage of organic matter and decomposition, biogeochemical cycling, and reduction of plant pathogens propagules are carried out in various ecological settings containing interacting organisms, including plants themselves (Janvier et al. 2007; Ansari and Mahmood 2019a, b). Today plant diseases are responsible for tremendous losses in different crops in both arable (Raaijmakers et al. 2009) and pastoral agriculture (Dignam et al. 2016). The nature of the complexity and how and to what extent good soil health affects disease progression continue to be deliberated.

Pastoral farming systems support the production of grazing livestock and cover more than 25% of the Earth's ice-free land surface (FAOSTAT 2011). Controlling plant disease is complicated by the multi-pathogen complexes that appear with annual, biennial, and perennial plants and the expansive nature and potentially challenging topography of pastoral-based agriculture systems, which impede delivery of external inputs (Ansari and Khan 2012a, b; Dignam et al. 2016). Naturally, disease-suppressive soils include consortia of beneficial microbes such as plant growth-promoting rhizobacteria (PGPR) involved in the protection of susceptible plant hosts from soil-borne disease (Mendes et al. 2011; Penton et al. 2014; Cha et al. 2016; Raaijmakers and Mazzola 2016; Ansari et al. 2017).

The phenomenon of general suppression is related to the competitive potential of the total soil microbial community; specific suppression is driven by the antagonistic activity of an individual or specific group of microorganisms (Weller et al. 2002; Raaijmakers and Mazzola 2016). The wealth of understanding correlated with the well-characterized models of soil suppressiveness in arable systems (Cha et al. 2016; Carrión et al. 2018) provides opportunities to explore and exploit mechanisms in pastoral agricultural systems. The latter improves our understanding of the processes that underlie release from pathogen pressure in natural grassland systems (Maron et al. 2011; Schnitzer et al. 2011; Latz et al. 2012, 2016; Mommer et al. 2018). Surprisingly, only a few studies have focused on the distribution of disease-suppressive microbiota in agricultural grasslands and the mechanisms by which these communities relate or respond to soil management practices (Dignam et al. 2016; Wakelin 2018).

Understanding soil physicochemical properties that affect microbial communities and their activities accentuates the design of management practices which steer ecosystem services (Nielsen et al. 2015). All plants and animals are subject to infection from one or more species of parasitic nematodes. Plant-parasitic nematodes cause heavy annual losses to major crops. Economic losses related to nematode infection would be greater without the application of effective strategies of nematode management and tactics that decrease losses.

A phylogenetically diverse range of soil microbial communities have been correlated with the suppression of plant diseases (Raaijmakers and Mazzola 2012). For instance, *Pseudomonas* spp. have been repeatedly implicated and are responsive to varying management practices across agricultural systems (Garbeva et al. 2004; van Overbeek et al. 2012; Walters et al. 2018; Mahmood et al. 2019; Ansari et al. 2020a, b).

Dignam et al. (2018) conducted in-depth molecular studies across pastoral soils to identify mechanisms by which indigenous soil microbes may be manipulated to improve the capacity of soil to suppress plant disease agents. Notably, variation in soil organic matter (SOM) quality has been positively correlated with both taxonomic (*Pseudomonas* community composition) and functional indicators of disease-suppressive activity in soils. Controlling practices that lead to significant alteration of soil organic matter content and quality (including chemical composition and decomposability) could devastatingly increase soil suppressiveness. Contributions of management-induced changes in biotic and abiotic soil properties to soil suppression have been studied. Previous measurements of soil organic matter quantity and consistency have been shown to vary with plant residue management (Simpson et al. 2012; Adair et al. 2013).

Due to environmental concerns, researchers have focused on finding suitable alternatives to chemical pesticides for controlling soil-borne pathogens and plant parasitic nematodes (Larkin et al. 1998; Yimer et al. 2018). In this context, alternative strategies including crop rotation, solarization, biofumigation, grafting, and application of biocontrol agents or organic amendments, such as composts, are of considerable interest among scientists and agricultural producers (Bailey and Lazarovits 2003; Louws et al. 2010a, b). The objective of the current chapter is to summarize the current knowledge of the most effective approaches used in the control of soil-borne diseases.

2.2 Management of Soil-Borne Pathogens

Biotic stressors including microbial pathogens, nematodes, and weeds attack different crops causing huge yield losses of 20 and 40% to global agricultural productivity. As such, these impediments are considered as the main obstacle in successful crop cultivation (Teng 1987; Oerke 2006). Soil-borne pathogens including fungi, bacteria, and nematodes are affected by physical, chemical, and biological properties of the soil and agricultural practices including irrigation, fertilization, and tillage regimes (Katan and Gamliel 2011). It is challenging to detect and diagnose a variety of soil-borne pathogens as responsible for serious plant diseases. Symptoms of soil-borne diseases, effected by different pathogens, are similar. Symptoms include root rot, root blackening, wilt, yellowing, stunting or seedling damping-off, bark cracking, and twig or branch dieback. Pathogens are well known as damaging factors due to extensive persistence even in the absence of host plants or suitable environmental conditions. Resistant structures such as cysts, sclerotia, chlamydospores, or oospores may be freely formed (Mihajlović et al. 2017). Yet the vitality of soil-borne pathogens varies and depends on prevailing environmental conditions. Thus, the majority of soil-borne pathogens cannot be controlled by a single approach. Many physical, chemical, and biological control strategies, such as that of use of host plant resistance, crop rotation, sanitation, and destruction of residual crop roots, nematicides, organic amendments, and use of eco-friendly fungi, bacteria, and other biological control agents have been reported to effectively control soil-borne pathogens (Fortuner 1991; Mihajlović et al. 2017).

One of the most effective approaches to disinfest soil is the application of steam or flooding the soil with hot water. The main disadvantage of these approaches is their high cost as they consume a high rate of fuel and involve expensive and sophisticated machinery (McGovern and McSorley 1997). Soil solarization, which involves heating the soil by solar energy, has proved to be a satisfactory alternative, bringing soil populations of pathogens to unharmful levels in areas with appropriate weather conditions (Basallote-Ureba and Melero-Vara 1993; Katan et al. 2012). Further, fumigants can be considered a major tool for soil disinfestation. However, certain fumigants are not readily degraded in soil and cause pollution of underground water and the environment (Mihajlović et al. 2017).

Disease suppression by biocontrol agents is the sustained manifestation of interactions among plant, pathogen, the biocontrol agent, the microbial community around the plant, and the physical conditions of the environment. Biological control of soil-borne diseases is complex because they occur in dynamic environments at the interface of root and growth media known as the rhizosphere. Rhizospheric microorganisms interact beneficially with their host plant via several mechanisms. They can promote plant growth directly by the improvement of nutrient acquisition or hormonal stimulation or indirectly affect plant health by reducing the severity of phytopathogens (Berg and Smalla 2009). The rhizosphere is subject to dramatic changes on a short temporal scale – including rain events and daytime drought. Changes result in fluctuations in salt concentration, pH, osmotic potential, water potential, and soil particle structure. The dynamic nature of the rhizosphere makes it an interesting setting for the interactions that lead to disease and biocontrol of disease (Waisel et al. 2002; Handelsman and Stabb 1996). Most plants exhibit inhibitory and stimulatory biochemical interactions with other plants and microorganisms, referred to as allelopathy. Root exudates of higher plants have the ability to affect microflora in the rhizosphere. Plants may secrete different bioactive compounds as root exudates that prevent phytopathogens from infecting crops. Medical plants play a vital role in controlling disease and negate the need for undesirable hazardous chemicals, thereby protecting the environment. Volatile essential oils extracted from medicinal plants have been reported to possess antimicrobial activity against a wide range of plant pathogens (Tanović et al. 2014). Further, oregano, fennel, and laurel oils demonstrate antimicrobial activity against soil-borne fungi of beans under laboratory conditions (Turkolmez and Soylu 2014).

2.3 Organic Additives Used with Crop Rotations

Organic matter and its replenishment have become the core of soil health management programs. Characteristics of the soil including physical, chemical, and biological properties are a function of organic matter content and quality. Adding organic matter to soil induces diverse and important biological activities (Widmer et al. 2002). Crop rotation practices and organic matter applications have the potentiality for the restoration of soil health and increased productivity of degraded highland crop fields.

Crop rotation undoubtedly provides multiple benefits during crop production. To minimize the severity of root-knot nematodes, the effectiveness of the application of botanical toxicants or plant product derivatives has been confirmed (Al-Askar 2012; Khalil et al. 2012; Ansari et al. 2019). Organic additives help preserve, sustain, or replenish soil resources, including organic matter, nitrogen, phosphorous, and nutrient inputs, as well accentuate physical and chemical properties (Ball et al. 2005; Ladygina and Hedlund 2010; Sasse et al. 2018). Crop rotation has a positive impact on soil fertility, condition, and aggregate stability. Small grains, especially barley, are highly recommended for improvement of organic matter content and reduction of problems from pink root and *Fusarium* basal plate rot of onion (Schwartz 2011). The most beneficial rotations in the family of *Brassicaceae* include that of broccoli, cabbage, cauliflower, turnip, radish, canola, rapeseed, and numerous mustards, which produce sulfur compounds that break down to produce isothiocyanates. The latter is toxic to a wide range of soil organisms and cleanse the soil as part of a process referred to as biofumigation (Youssef and Lashein 2013). Further, crop rotation strategy improves soil water management and reduces erosion (Ball et al. 2005). However, crop rotation is not useful in the management of diseases caused by soil-borne pathogens that possess a wide host range and those that form long-living survival structures, such as sclerotia, cysts, or oospores (Umaerus et al. 1989). In addition, crop rotation does not affect disease organisms that survive on or in the seed, such as cereal smuts. Equally, crop rotation does not affect disease organisms that blow in, such as cereal rusts (Kheyrodin 2011). Application of crop rotation used in combination with other controlling strategies is highly recommended.

2.4 Biological Control

Biological control is defined as the antagonistic effect of organisms which act as biocontrol agents against soil-borne pathogens (Afzal et al. 2013; Ansari et al. 2017; Berendsen et al. 2018; Ansari et al. 2020a, b). Usually, biocontrol agents are applied individually to control the proliferation of different plant pathogens. While some studies reported the potential benefits of a single application of biocontrol agents, in many other cases studies report insignificant results because a single biocontrol agent may not be active in all types of soil environments and agricultural ecosystems (Raupach and Kloepper 1998). These result in insufficient colonization of the agents, low tolerance to changes in environmental conditions, and variability in the production of antifungal metabolites (Weller et al. 2002). Mixtures of biocontrol agents have the advantage of activity with broad-spectrum properties.

Mixed applications significantly enhance the efficacy and reliability of biocontrol agents and maximize the induction of defense enzymes in plants (Latha et al. 2009). The main character of an effective biocontrol strain is its ability to compete and persist in the environment and to colonize, proliferate, and establish itself on plant parts. Furthermore it should be affordable to produce strains at a large scale and maintain good vitality without specialized storage systems (Harman 1996; Lamovsek et al. 2013). Soil application of biocontrol agents, viz., *Trichoderma viride*, *T. harzianum*, fluorescent *Pseudomonas*, *Serratia marcescens*, and *Bacillus subtilis*, effectively decreases the severity of root rot diseases caused by soil-borne pathogens in numerous economic crops (Loganathan et al. 2010; Shafique et al. 2015b). *Trichoderma* spp. are endophytic fungi which grow in plant tissue without causing disease and are well known to secrete large quantities of toxic metabolites such as gliotoxins which have antifungal activity. The antagonistic activity of *Trichoderma* spp. is related to direct mycoparasitism in addition to competition for nutrients and space (Sharon et al. 2001; Afzal et al. 2013). Thus, *Trichoderma* spp. are mycoparasites that have been considered as powerful biocontrol agents for foliar and soil-borne pathogens as well as species of plant-parasitic nematodes (Kowsari et al. 2014). Species of *Trichoderma* such as *T. harzianum*, *T. asperelloides*, and *T. hamatum* have proven nematicidal potentiality against root-knot nematodes (Sharon et al. 2001; Sayed et al. 2019) and can be developed for introduction as strong biocontrol agents. Increasingly, *Trichoderma* spp. are evaluated for their activity against root-knot nematodes on a wide range of crops, such as okra, tomato, mung bean, cucumber, bell pepper, and sugar beet (Meyer et al. 2001). Afzal et al. (2013) reported that *T. viride* is effective in inhibiting *F. solani*, *F. oxysporum*, and root-knot nematodes on okra, used alone or in combination with *Pseudomonas aeruginosa*. However, variations in efficacy of isolates**,** biocontrol ability, and reproducibility of consistent results and effects under variable environmental conditions hinder their development and application at a large scale (Sharon et al. 2001).

Different species of bacteria and actinobacteria can be applied more easily and have proven satisfactory in the control of soil-borne diseases (Ramarathnam et al. 2011). The bioactivity of the pigment extracted from *Serratia marcescens* was shown to inhibit the vitality of nematodes at their juvenile stage (Rahul et al. 2014). Furthermore, *S. marcescens* secrete hydrolytic enzymes (proteases, chitinases, lipases, and cellulases), which result in severe deformities in fungal mycelia and play a role in controlling root rot disease in tea after field application (Purkayastha et al. 2018).

Actinobacteria are important saprophytes which have the ability to degrade a wide range of plant and animal debris in the process of decomposition. Certain genera, such as *Streptomyces* and *Micromonospora*, are known for producing bioactive metabolites including enzymes and antibiotics with broad-spectrum properties. *Streptomyces asterosporus*, an endophytic actinobacteria, produces large quantities

Table 2.1 Common microorganisms used as biocontrol agents against soil-borne diseases

Plant pathogen	Host	Biocontrol agent	References
Sclerotium rolfsii	Sugar beet	*Trichoderma harzianum*	Paramasivan et al. (2014)
Fusarium oxysporum f. sp. ciceris	Chickpea	*Pseudomonas; Bacillus* spp.	Karimi et al. (2012)
Rhizoctonia solani	Tomato	*Trichoderma harzianum*; *Serratia proteamaculans*	Youssef et al. (2016)
Ralstonia solanacearum	Tomato	*Streptomyces microflavus*	Shen et al. (2020)
Meloidogyne spp.	Tomato, Cucumbers	*T. harzianum*, *T. asperelloides* and *T. hamatum*, *T. viride* *Paecilomyces lilacinus*	Sayed et al. (2019) and Yankova et al. (2014)
Heterodera schachtii	Sugar beet	*T. harzianum* and *T. virens*	Moghadam et al. (2009)

of hydrogen cyanide, siderophores, chitinases, and β-1,3-glucanases. These actinobacteria significantly inhibit *Fusarium* root rot disease severity in tomato seedlings (Goudjal et al. 2016). Furthermore *S. antibioticus* showed nematicidal activity against *Meloidogyne incognita* with the culture supernatant of the strain inducing 100% juvenile mortality. This significant nematicidal activity may be related to actinomycins secreted by *Streptomyces* antibiotics as part of an important secondary metabolite production (Sharma et al. 2019). Biological control can be considered as a safe and effective alternative strategy to reduce the heavy use of harmful chemical pesticides. Common biocontrol agents are laid out in Table 2.1.

2.5 Nanomaterials as a New Approach for the Management of Soil-Borne Pathogens

Nanotechnology is an intriguing and rapidly advancing science and has the potential to revolutionize many scientific, technological, medical, and agricultural disciplines (Khan and Rizvi 2014). Nanotechnology has potential use in the management of plant diseases. The most simple and obvious way to protect plants from pathogen invasion is the direct application of nanoparticles in the soil, on seeds, or on foliage. Their effects on non-target organisms, particularly mineral fixing/solubilizing microorganisms, will be of great importance in the direct application of nanoparticles in soil.

Different types of nanomaterials including carbon tubes and cups can be utilized as carriers for valuable chemicals such as pheromones, systemic acquired resistance (SAR) inducing chemicals, polyamine synthesis inhibitors, or even concentrated active ingredients of pesticides, due to their controlled release under flooded conditions (Khan et al. 2014a). Impacts should be addressed to determine the scope and use of nanoparticles (NPs) in the control of plant diseases from two main perspectives: the direct effect of NPs on pathogens and the use of nanomaterials in pesticide formulation, namely, “nanopesticides.”

NPs may prove very useful in the diagnosis of plant pathogens/diseases and pesticide residue analysis, considering the ultra-small size of the particles and their high degree of reactivity/sensitivity. Moreover, one of the nanomaterial techniques – nanoencapsulation – applies to antioxidants and antimicrobials, identified as colloid-based nano-incorporation collaboration. Lipid-based nanoencapsulation techniques of encapsulation are based on biologically derived polymeric nanocarriers. Further encapsulation techniques are based on non-biological polymeric nanocarriers, incorporation of cyclodextrin, electrospraying, electrospinning, carbon nanotubes, and nanocomposite encapsulation.

In the control of soil-borne pathogens, several researchers address the effect of nanoencapsulation techniques on antioxidant/antimicrobial function. Pisoschi et al. (2018) emphasizes the importance of selecting the right encapsulation form. Bioactive compound safety and controlled release are accomplished, but consideration should be given to the effect of nanomaterials on human health and the environment. The rise, retention, or decrease of bioactivity depends on relationships formed between the encapsulated compound functional groups and the encapsulating nanomaterial.

2.6 The Mechanisms of Nanomaterials for Management of Soil-Borne Pathogens

The main mechanism of action resulted from nanoparticles in antimicrobials and pesticides is that of reactive oxygen species (ROS), which induce oxidative stress and release superoxide, free radicals, and particles that can react and upset peptide interactions in the cell wall of microscopic organisms (Makhluf et al. 2005). ATP is synthesized by the reduction of molecular oxygen to water in the mitochondria of cells by a series of coupled proton and electron transfer reactions. A small percentage of oxygen is not entirely reduced during this process, resulting in the formation of superoxide anion radicals and consequently other radicals containing oxygen. Therefore, ROS require results from alleging oxidative metabolism for cell division, most of which happens in the mitochondria. Superoxide anion radicals, hydroxyl radicals, singlet oxygen, and hydrogen peroxide (H_2O_2) comprise biologically important ROS (Yin et al. 2012; Prasad et al. 2017). Via intense oxidative stress, the blast of ROS causes damage to all the macromolecules of the cell causing lipid peroxidation, protein modification, enzyme interruption, and degradation of ribonucleic acids (RNA) and deoxyribonucleic acids (DNA). ROS contributes to cell death at high concentrations and induces severe DNA disruption and mutations at low concentrations, in bacteria and other cellular systems present in soil environments (Wang et al. 2011; Matějka and Tokarský 2014).

Nanoparticles cannot cross the nuclear membrane and so accumulate in the cytoplasm where, as the nuclear membrane breaks down, they obtain entry to the nucleus during mitosis (Singh et al. 2009). The direct interaction of nanoparticles with proteins associated with RNA and DNA can result in the genetic material being physically affected. Another cause for DNA disruption may be interaction with the structure or action of the DNA repair enzymes in cell nuclei.

Nanoparticles are unable to reach the nuclear membrane and thus aggregate in the cytoplasm, where, when the nuclear membrane divides, they can access the heart amid mitosis (Singh et al. 2009). Physical degradation of nucleic acids can result from the direct interaction of nanoparticles with DNA and DNA-related proteins. An additional cause for DNA disruption may be interaction with the structure or role of the DNA repair enzymes in the nucleus (Huang et al. 2015; Mostafa et al. 2018).

In Fig. 2.1 nanoparticles enter the cell via endocytosis and release ions that induce the formation of ROS. ROS products cause many damages within the cell and eventually cause cell death: (a) DNA denaturation and damage, (b) unfolded protein and damaging, (c) mitochondria dysfunction, and (d) lipid peroxidation, cell membrane disruption, and intracellular content leakage.

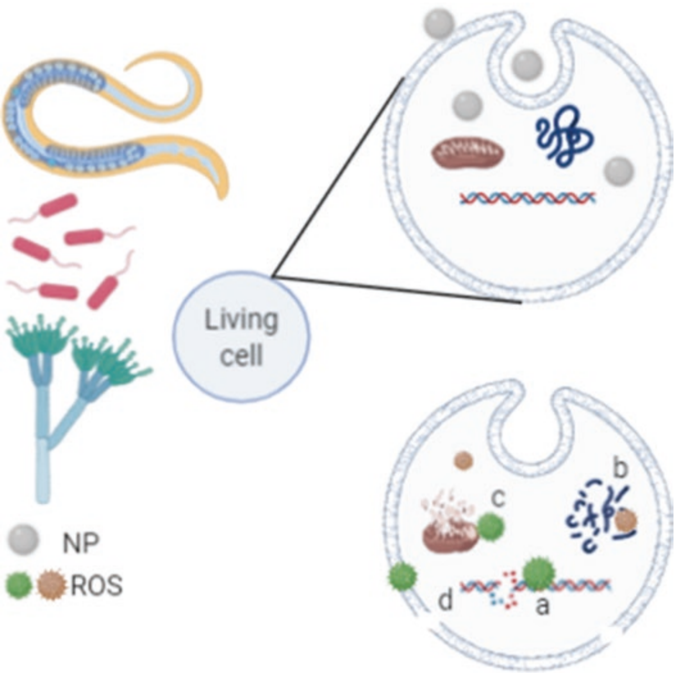

Fig. 2.1 Possible mechanisms of nanoparticle pesticides

2.7 Effect of Nanoparticles on Plant Pathogens and Microorganisms

The physiochemical properties of nanoforms differ greatly from their macro-forms; it is important to analyze the impact of NPs on microorganisms in order to take advantage of this technology in plant protection, particularly for phytopathogens. The behavior of microorganisms may be impaired by nanoparticles due to their ultra-small size and reactivity.

Inhibition of colonization of *Staphylococcus aureus*, *P. aeruginosa*, *Escherichia coli*, and *Klebsiella pneumoniae* has been achieved using silver NPs (Logeswari et al. 2015). Silver nanoparticles (30 nm) synthesized with *Solanum trilobatum* and *Ocimum tenuiflorum* leaf extracts have high antimicrobial activity against *S. aureus* and *E. coli*, respectively (Logeswari et al. 2015). The available evidence so far on this aspect has demonstrated that the nanoparticles have a significant impact on bacteria and fungal colonization. Such effects, however, are suppressive and also stimulatory and should not be generalized.

2.7.1 Effect of Nanoparticles on Bacteria

The antibacterial effect of zinc nanoparticles has been extensively studied by Jayaseelan et al. (2012) against *P. aeruginosa*. The maximum inhibition zone for bacteria colonization (22 ± 1.8 mm) was reported at 25 ng mL^{-1}ZnO NPs. So, a new antimicrobial compound was revealed by ZnO NPs action. Bryaskova et al. (2011) examined the antibacterial action of synthesized Ag NPs/PVP (polyvinylpyrrolidone-based hybrid materials with silver nanoparticles) against three distinct classes of bacteria, *Staphylococcus aureus* (gram-positive bacteria), *E. coli* (gram-negative bacteria), and *P. aeruginosa* (gram-negative non-fermentable bacteria), and also against *B. subtilis* spores.

The efficacy of CuO NPs as antimicrobials has been identified by Azam et al. (2012) against *S. aureus*, *B. subtilis*, *P. aeruginosa*, and *E. coli*. Guzman et al. (2009) noted that silver nanoparticles displayed elevated antimicrobial and bactericidal behavior against extremely methicillin-resistant strains of bacteria such as *E. coli*, *P. aeruginosa*, and *S. aureus*. In general, it has been observed that the antibacterial behavior of nanoparticles is dependent on the concentration, morphology, metabolism, membrane intracellular selective permeability, and the form of the microbial cell.

2.7.2 Effect of Nanoparticles on Plant Pathogenic Fungi

In the processing of food products, plant pathogens, bacteria, fungi, viruses, and nematodes, provide major limitations (Khan et al. 2011, 2012; Khan 2012a; Khan and Jairajpuri 2010a, b, 2012). The exploitation of nanotechnology for the treatment of plant pathogens has great potential. Deepak et al. (2013) report that $CuSO_4$ and $Na_2B_4O_7$ were found to be most successful in controlling rust disease of field peas among nanoforms of 15 micronutrients. Sunflower damping-off and charcoal rot diseases were suppressed by microelements including manganese and zinc (Abd El-Hai et al. 2009).

Nanoparticles of silver have a fungicidal effect against various yeasts and molds, different strains of *Candida*, and *Aspergillus brasiliensis* (Bryaskova et al. 2011). The fungicidal effectiveness of ZnO NPs has been reported against post-harvest pathogenic fungi *Botrytis cinerea* and *Penicillium expansum* (He et al. 2011). To investigate antifungal activities of ZnO NPs and to classify variations in morphology and cellular compositions of fungal hyphae, conventional microbiological plating, scanning electron microscopy (SEM), and Raman spectroscopy have been used. At concentrations greater than 3 mmol L^{-1}, ZnO NPs (70 ± 15 nm) inhibited the growth of both *B. cinerea* and *P. expansum*. In the hyphae of *B. cinerea*, the NP treatments induce deformation and stopped the growth of conidiophores as well as conidia in *P. expansum*, which inevitably contributes toward the death of fungal hyphae.

Plant pathogenic fungi (*Alternaria alternata*, *Sclerotinia sclerotiorum*, *Macrophomina phaseolina*, *Rhizoctonia solani*, *B. cinerea*, and *Curvularia lunata*) have been shown to be significantly inhibited by a concentration of 15 mg L^{-1} of silver NPs (Krishnaraj et al. 2012). Further, suppression of colonization of *A. flavus* has been achieved with the use of zinc nanoparticles at 25 mg mL^{-1} (Jayaseelan et al. 2012).

2.7.3 Effect of Nanoparticles on Plant Pathogenic Nematodes

The emerging branch of bionanotechnology combines biological principles with chemical and physical approaches for the production of nano-sized particles with specific functions. Bionanotechnology is an economic substitute for physical and chemical methods of nanoparticle formation (Ahmed et al. 2006). The synthesis of metal nanoparticles with greener methods and its application in biological fields are flourishing fields of research (Narayanan and Park 2014). Three types of nanoparticles, silicon oxide (SiO_2NP, 11–14 nm), silver (AgNP, 20 nm), and titanium oxide (TiO_2NP, 20 nm), have been shown to be toxic to *M. incognita*, in in vitro and in vivo experimentation on tomato (Ardakani 2013). The smaller size of the nanoparticles with a large surface area increases interactions with microbial cells to implement a broad range of potential antimicrobial activities (Martinez et al. 2010).

The effect of AgNPs has been evaluated for their potential nematicidal effects on *M. incognita* infecting tomato (Ahmed El-Deen and Bahig 2018; El-Batal et al. 2019; Kalaiselvi et al. 2019). Further, ZnO NPs have an inverse effect on the cuticle and hypodermis of nematodes by affecting lipid, glycogen, and mucopolysaccharides (Siddiqui et al. 2018). Further, gold nanoparticles show promise in the management of root-knot nematodes (Thakur et al. 2018; Hu et al. 2018).

2.7.4 Nanopesticides

The presence of a formulation containing an active ingredient applied around the plant root at the initial crop growth stage helps in protecting the plant from the invasion of pathogens and bringing its population down below economic threshold levels (Khan et al. 2014a, b). As all the propagules/spores of a pathogen do not invade the host at one time, within their intermittent attack, consequent persistence or gradual release of an active ingredient in the root zone improves effectiveness of formulations (Khan et al. 2011). Furthermore, timely and slow release of an active element decreases the amount of pesticide required for disease control. Such controlled release has the added benefit of prior minimization of the effects of the pesticide on man and the environment (Khan and Jairajpuri 2012).

Controlled release of active ingredients may be achieved through a nanotechnological method in which nanomaterials act as a carrier for the chemicals. Hence refined formulations potentially reduce pesticide inputs associated with environmental hazards, namely, disease vectors and parasitic organisms. Nanopesticides decrease application rates as chemical quantities required are effective in the order of 10–15 times smaller than those applied through classical formulations. Hence higher efficiency is achieved for sufficient control of diseases. With a smaller size, better kinetic stabilization, low viscosity, and optical transparency, nanoemulsions improve pesticide delivery systems (Xu et al. 2010). As a carrier for pesticide delivery, nanoemulsions enhance bioavailability and solubility of the active ingredients of chemicals. Thus nanopesticides have very small particles of active ingredients or other small engineered structures with pesticide properties (Bergeson 2010b). Furthermore, nanopesticides enhance the release and wettability of agricultural formulations and the movement of unwanted pesticides (Bergeson 2010a).

Nanomaterials and biocomposites show beneficial properties such as permeability, stiffness, crystallinity, solubility, thermal stability, and biodegradability (Bouwmeester et al. 2009; Bordes et al. 2009), necessary for the formation of nanopesticides. Nanopesticide formulations present an enormous specific surface area and accordingly have an increased affinity to target molecules (Yan et al. 2015). Nanopesticide delivery techniques such as nanoencapsulation, nanoemulsions, nanocages, and nanocontainers show effectiveness in plant protection programs (Bouwmeester et al. 2009; Lyons and Scrinis 2009; Bergeson 2010b). Corradini et al. (2010) examined the prospect of using chitosan nanoparticles, an extremely degradable antibacterial, for the slow release of NPK fertilizer. Further, kaolin clay-based nanolayers have been developed to be used as cementing and coating material for the controlled release of fertilizers (Liu et al. 2006). Principally, nano-clay materials provide interacting surfaces with high aspect ratios for encapsulation which facilitates their use as agrochemicals such as fertilizers, plant growth promoters, and pesticides (Ghormade et al. 2011). In general, there are three types of controlled release systems (CRS): zero-order, first-order, and square-root time release, each of which may be tailored to environmental conditions and pest/pathogen biology. Nano-formulations are released faster in the soil, yet slowly in plants with residue levels below regulatory criteria in foodstuffs.

2.8 Integrated Approaches of Soil Management

After a century of incremental research, technological advances are connecting with a need for sustainable crop growth, leading to yield increases. Severe diseases in many crops are caused by soil-borne pathogens which have combined lineaments based on their close connections with the soil. Interactions between the pathogen and the host, in turn, interact between both biotic and abiotic environmental components.

Basic management strategies employed to condition and improve soil include disruption of one or more of the disease components, at any stage of disease development, to achieve an economic depression in diseases with minimal disturbance to the environment (Katan 2017; Mihajlović et al. 2017). Soil management is achieved through physical, biological, cultural, physiological, chemical, and genetic approaches. Further, management may utilize soil disinfestations via biofumigation, fumigation, anaerobic soil disinfestation, or soil solarization. Interestingly, application of fungicides, organic amendments, biocontrol, crop rotation, resistant cultivars, grafting, induced resistance, and cultural practices may be combined in integrated pest management programs.

Integrated pest management (IPM) of soil-borne pathogens aims to combine control approaches in an environmentally optimal manner for rational and sustainable disease reduction (Porter et al. 2010). IPM aims to achieve sustainable increases in yields and income development in terms of plant diseases with low negative effects on environmental and natural resources while facilitating a reduction of pesticide use. A systematic approach to sustainable pest management has been illustrated. Lewis et al. (1997) mention that long-term resolutions for pest management may only be carried out by restructuring and managing methods that maximize an array of built-in preventative strengths, with therapeutic strategies. Further, Chellemi et al. (2016) indicate four pillars in the management of soil-borne pathogens which seek to prevent the introduction and separation of pathogens into the crop systems and reduce pathogen populations to manageable levels.

Soil disinfestation should incorporate an effective reduction of soil pest populations with minimal damage to soil microbial and beneficial activities, such as mycorrhizae. Importantly, disinfestation should not leave phytotoxic residues (Katan 2017). Soil solarization effects mild soil heating (45–55 °C) in upper soil layers at depths of 5–20 cm and 35–40 °C in lower (30–45 cm) layers. Solarization works best on heavy soils containing clay, loam, or mixtures of the two. These soils hold more water than light soils, enabling steam production every day. Steam is required to kill nematodes, weed seeds, and insect eggs in the soil. Solarization may be less effective on sandy soil, which drains faster and produces less steam. To maximize the benefit of solarization in sandy soils, drip irrigation lines should be laid under clear plastic covers with water added regularly. The warming of the soil has no radical effect on resident biotic components. However, it results in the physical thermal killing of pathogens in upper, hotter soil layers and stimulates a beneficial microbial shift in the less heated soil layers, which contributes to pathogen control (Culman et al. 2006; Gelsomino and Cacco 2006; Ozylmaz et al. 2016).

Breeding potential plant hosts for resistance to pests/pathogens is a very effective method for controlling pathogens with no negative effects on the environment. Further, grafting scions of commercially desirable but susceptible cultivars on rootstocks resistant to soil-borne pathogens supplies plants with functional resistance that is equal to non-grafted cultivars with genes for resistance. The grafting approach provides pliability because it is relatively easier and faster to replace a rootstock, when a new physiological race appears than to breed a new cultivar (Louws et al. 2010a, b; Mihajlović et al. 2016).

Novel approaches of transferring genes across plant breeding barriers, particularly including wild species, and inclusion of resistance controlled by multiple genes offer tremendous resources for soil-borne pathogen resistance. Isolating and cloning genes of resistance can facilitate direct gene transfer within and across crop species. Our limited understanding of soil-borne pathogen genetics relates to relative disease responses overtime on resistant crops and advances only through research at the molecular, organismal, and population levels. A better understanding of these processes is fundamental for the wise deployment of resistant cultivars in cropping systems. Furthermore, the application of organic amendments has been suggested for management of soil-borne disease strategies (Bonanomi et al. 2010).

Organic amendments, such as animal and green manure, peats, composts, and organic wastes, are viable propositions to control soil-borne diseases (Colla et al. 2012; Arnault et al. 2013; Mehta et al. 2014). Crop rotation gives various benefits to crop production. As mentioned in Sect. 2.3, rotations are associated with enhanced soil productivity, increased soil tilth, reduced erosion, improved soil water management, and aggregate stability and textural improvement (Li et al. 2020). Crop rotation is without a doubt a valuable method for plant disease management. Although ineffective when used singularly, reductions in disease caused by soil-borne pathogens that have a wide host range or produce long-living survival structures occur (Tillmann et al. 2016). Soil pesticides may be used with seedling diseases because of the need to protect plants for relatively short periods (Chase 2012).

Different approaches of management of soil-borne pathogens are summarized in Fig. 2.2.

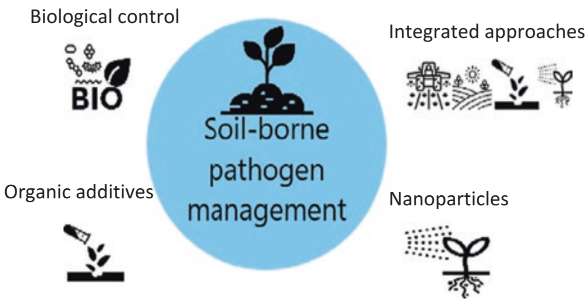

Fig. 2.2 Sustainable management of soil-borne plant pathogens

2.9 Using Soil-Borne Pathogen Biodiversity to Contribute to Sustainable Agriculture

Research is in demand to identify, select, and adopt cropping systems (including cover crops, antagonistic crops, green manure crops, inter-planting, rotations, organic amendments, and minimal tillage) that improve the soil diversity of pathogens and other fauna and microflora and repress known species of plant-parasites in agroecosystems. Much could be learned from the "biological balance" in the natural ecosystem, which affects fewer changes in the physical and biotic environment. Future soil-borne pathogen management must utilize sustainable agricultural practices that take into account beneficial, detrimental, and other soil-borne pathogens species in the rhizosphere and soil.

2.10 Conclusions and Future Prospects

Nowadays, the main impediment in crop production is the lack of successful and safe opportunities for controlling soil-borne diseases. The application of single approaches to control soil-borne diseases is not sufficient. Non-chemical options, such as soil solarization, crop rotation, soil amendments, or even biological control, may be ineffective when applied alone. However, all of these when used in combination become viable as components of an integrated pest management strategy, although they do not completely eliminate pathogens from the soil. Initial results obtained by combining different methods for the control of soil-borne diseases imply a necessity to continue research in this area in order to ensure long-lasting sustainability of crop protection. This chapter described a group of eco-friendly approaches that may be effective when used in combination to control a wide range of soil-borne diseases.

In conclusion, the introduction of chemical fertilizers and pesticides for the management of the soil-borne disease can result in good yield. However, a wide range of human diseases and ecological perturbations may be encountered. The biological control of soil-borne disease is an alternative approach to counter further biodiversity loss. The application of biocontrol agents and organic additives not only improves soil fertility but also controls disease. Recently, nanoparticles have been introduced in the intensification of agricultural crop production. Judicious application of nanomaterials along with biocontrol agents and organic additives is likely to exhibit better results in terms of plant disease management and crop produce intensification in sustainable cropping systems.

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