Sustainability in Plant and Crop Protection 18

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Sustainable Management of Nematodes in Agriculture, Vol.1: Organic Management

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The series describes new perspectives recently developed in pest and disease management, based on innovative tools emerging from basic and applied research. The volumes will aim at interested readers involved in plant protection and crop management, for whom soil biodiversity, crop sustainability and, in general, organic approaches are fundamental. Different cropping systems will be treated by researchers involved in cutting edge studies worldwide. A number of basic issues including sustainability, life-cycle assessment, evolution, plant nutrition and organic cropping technologies will provide a common framework, within which different components of the crop production cycle will be focused on. These will range from roots and endophytes to pest and disease control, through the management of soil microbiome and fertility. These issues will be examined at the field and crop levels, including the effects of invasive species and climate changes on agroecosystems. Recent advancements in massive sequencing will represent the basis of dedicated volumes, dealing with transcriptomics and related approaches. They will illustrate the potentials and benefits of extensive DNA and RNA data analyses and studies, for practical purposes in crop protection, disease management and food production.

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Sustainable Management of Nematodes in Agriculture, Vol.1: Organic Management

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Preface

Plant parasitic nematodes cause considerable losses to agricultural crops, globally. The estimated yield loss due to these tiny pests is more than US$ 150 billion annually. In terms of percentage, this estimated global yield loss is around 10% annually. In order to fulfill the demand of growing population, significant technological efforts are being made to provide sustained agricultural productions that may also include use of synthetic nematicides. Majority of farmers actually use such nematicides to safeguard the food and commercial products they produce. Synthetic nematicides are effective and are known to reduce the nematode population in agro-ecosystem in a short term. However, their extensive and indiscriminate use poses human health and environmental problems. Nematicides exposure is one of the foremost concerns about environmental safety worldwide. Continued exposure either through food products and fodders or through work exposure is currently posing a severe health hazard throughout the world. In the process of making decisions concerning the usage of nematicides, both new and old, risk assessment remains critical. Considering the ill effects of synthetic nematicides and rising concerns about economic and ecological consequences of their use, global research efforts are looking for environment-benevolent and sustainable alternative approaches for nematode control in sustainable agriculture.

Organic amendment is one of the promising strategies that can play a significant role in sustainable nematode management, building up at the same time the soil fertility for sustainable agriculture. Various research efforts have highlighted the potential role of different organic amendments. These include green manures, animal manures, composts, plant products, and essential oil, among others, applied in effective nematode management strategies and improving plant growth. In addition, investigation on agricultural wastes, such as dried-crop residues, and industrial by-products, such as oil cakes, sawdust, cellulosic waste, and sugar-cane bagasse, has provided encouraging results. These organic amendments can contribute to the suppression of plant parasitic nematodes directly or indirectly, through their effects on nematode eggs, juveniles, and adults. They can also inhibit the nematode population by sustainable, although temporary, changes in soil physicochemical properties, including pH and organic matter. It is therefore important to know the influence mechanism of organic amendments on nematode suppression.

In spite of the established potential of organic amendments in sustainable nematode management, the scientific information on the topic is scanty. The present volume, *Organic Management of Nematodes in Agriculture*, therefore, is an endeavor to synthesize the latest, in-depth, and critical information on the organic products available today for nematode management. Here, we provide 16 chapters contributed by international professionals divided into two parts. Part I, with eight chapters, covers paradigms and mechanisms of nematode management through organic means. Part II, comprising of eight chapters, deals with the applied aspects of organic nematodes management and regional case studies/success stories. We believe that the present volume provides a balanced view of basic as well as applied aspects that will be useful to students, researchers, and scholars working in the field of sustainable nematode management. Further, we consider that the data and information herein gathered and discussed will assist policy makers and administrative authorities all over the world, when regulating sustainable nematode management strategies, thereby minimizing use of chemicals-based approaches.

The volume editors would like to express their sincere gratitude to all contributors for submitting their work and timely responding to all the post-submission editorial queries. We have received numerous insightful and constructive inputs from researchers all across the world on this subject while editing this book, for which we are sincerely grateful to them. It was indeed a memorable experience reading through the exciting knowledge synthesized by the authors in their chapters. We would also like to thank the editorial as well as production team at Springer, particularly Mr. Prasad Gurunadham (Project Coordinator, Books), Zuzana Bernhart (Executive Editor, Plant Sciences – Books), Mariska Van Der Stigchel, and Albert Paap, for their critical evaluation, encouragement, and constant whole-hearted support.

Dr. Kamal K. Chaudhary would like to place on record his deep sense of gratitude to his research mentor late Dr. R. K. Kaul, Principal Scientist, Central Arid Zone Research Institute, Jodhpur, for his guidance and training, which was the motivation to bring this volume as a tribute to the Indian nematologist par excellence. Dr. Chaudhary also wishes to thank his family members, Mrs. Kesher (mother), Mrs. Manju Chaudhary (wife), Mr. Pulkit Chaudhary (son), and Miss Jyoti Chaudhary (daughter), for their unconditional love, patience, encouragement, and incredible support during this period. Last but not the least, Dr. Chaudhary also wishes to thank all friends, staff members, and relatives for their encouragement during the entire editing tenure.

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Last but not the least, the volume editors wish to thank Dr. Aurelio Ciancio, Series Editor – Sustainability in Plant and Crop Protection, for his critical evaluation, constant support, and encouragement.

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Contents

Part I
Organic Management of Nematodes: Paradigms and Mechanisms

Chapter 1
Use of Natural and Residual Resources for the Sustainable Management of Phytonematodes: Challenges and Future Trends

Thales Lima Rocha, Vera Lucia Perussi Polez, Lívia Cristina de Souza Viol, Reinaldo Rodrigues Pimentel, Danielle Biscaia, and Jadir Borges Pinheiro

Abstract The growing demand for safe food associated with increased restrictions for the use of synthetic agrochemicals in different cultures has led to the development of more sustainable technologies for control of pests, such as phytonematodes. In this sense, natural products and residues are rich sources of compounds and nutrients that can contribute to productivity and the control of these phytoparasites. Thus, this chapter presents the scientific bases, examples of success, mechanisms of action, advantages and disadvantages regarding the use of: (i) botanical and fungal resources; (ii) management with cover crop and industrial plant residues; (iii) resources from animals and agro-industrial wastes; and (iv) blends. Additionally, a discussion concerning natural or recycled products is proposed, indicating the challenges and trends. In this context, challenges concern: (i) biodiversity conservation, (ii) quality system (e.g. rules and standardization) to guarantee reproducibility, repeatability, reliability, stability, efficiency, and safety, (iii) government policies, (iv) market regulations, public and private institutions integration. Finally, we discuss trends regarding nanotechnology-based green chemistry,, the use of blenders, the Integrated as well as Holistic Pest Management. These trends together integrate

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the farmer in designing solutions for pest control, minimizing socioeconomic and environmental impacts, and customer satisfaction.

Keywords Phytonematodes · Control · Biopesticides · Plant extracts · Essential oil · Fungi extracts · Cover-crop plants · Agro-industrial waste · Blends

1.1 Introduction

World agriculture provides food for billion human beings. In this sense, population growth has required strategies that allow an increase in food productivity to ensure global food availability (The State of the World's Biodiversity for Food and Agriculture, 2019). However, one of the central challenges in food production is pest control. Among them, plant-parasitic nematodes such as root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Heterodera* spp. and *Globodera* spp.), and lesion nematodes (*Pratylenchus* spp.) represent one of the main causes of annual crop losses (Jones et al., 2013). These phytoparasites (Fig. 1.1) affect several crops with high added value and, therefore, cause global annual losses on the order of million dollars (Mesa-Valle et al., 2020).

Currently, the main strategy of nematode control is the use of synthetic nematicides (Lengai et al., 2020). However, most of these agrochemicals are potentially toxic to both human and animal health and the environment. For this reason, the use of many nematocides has been restricted in several countries (EC, 2013; USEPA, 2009).

To overcome this limitation, and also to ensure the availability of safer food supplies, several strategies have been developed. Among them, the use of plant and fungus resources, animal and plant agro-industrial residues, the Integrated Pest Management (IPM), and blends provided some options with a great potential for applicability.

In a "green" chemistry èersèective, the use of sustainable technologies with biocidal action aimed at reducing or minimizing the adverse impacts of toxic products on farmers and consumers health, as well as the environment. In this sense, the quality and safety of agricultural products are a worldwide trend. It is worth mentioning that, throughout this process, the social awareness for consumption of safe and environmentally low impact food has been crucial. This social movement has contributed in the last decades to major changes in the industry and market of conventional pesticides.

Global biodiversity and its ecosystems constitute a very rich source of biologically active materials which could be used in traditional crop protection (The State of the World's Biodiversity for Food and Agriculture, 2019). In this context, Brazil biodiversity resourcescan generate global proactivity in the areas of science, technology, and innovation through a number of biological inputs for sustainable agriculture. It offers a great opportunity to explore new molecules, to find out possible distinct functions as well applications. These varieties of molecules can be obtained

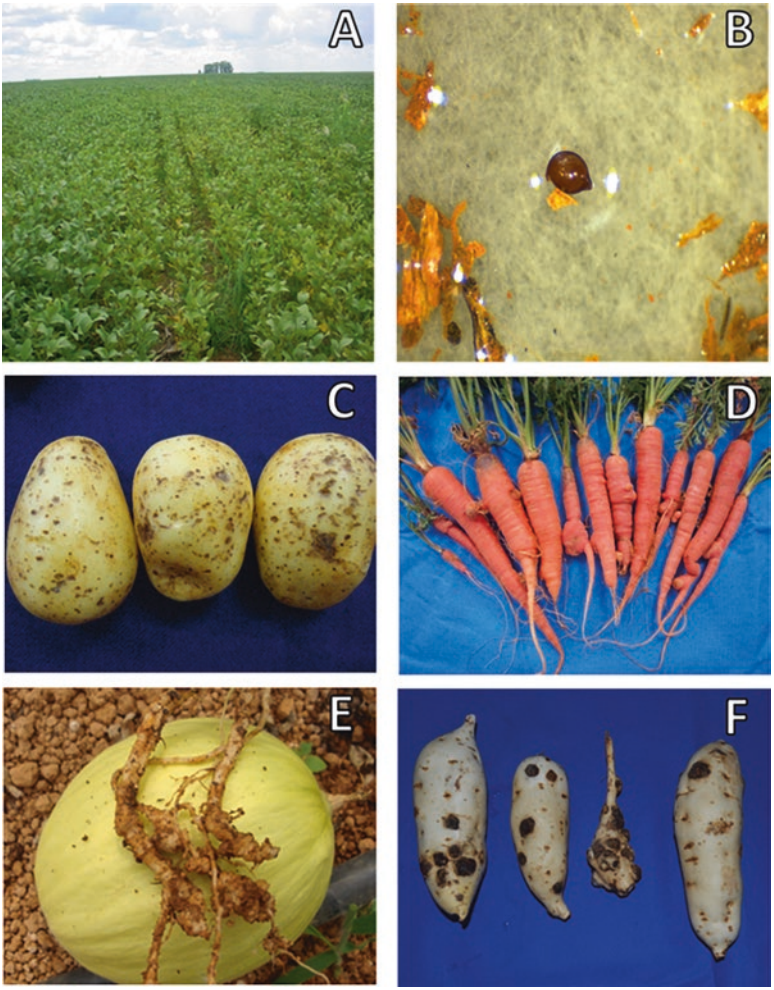

Fig. 1.1 Soybean field exhibiting plants with stunting and yellowing, or symptoms of chlorosis due to infestation by soybean cyst nematodea (*Heterodera glycines*) (**a**); Nematode resistance structure: cyst of *Heterodera glycines* (**b**); Symptoms in potato tubers due to infestation by a root-lesion nematode (*Pratylenchus* spp.) (**c**); Symptoms in carrot roots due to the presence of root-knot nematodes (*Meloidogyne* spp.) (**d**); Melon roots showing galls (**e**) due to parasitism by a *Meloidogyne*s sp. Symptoms in white sweet potato roots caused by *Meloidogyne* sp. (**f**). (Authors: Danielle Biscaia and Jadir Borges Pinheiro)

by prospecting different biomes and/or germplasm or microorganism banks. In addition to these sources, animal and agro-industrial wastes also represent another important source of potentially useful molecules. Thus, natural resources and residues are important sources of complex molecules, with a high capacity to interact with different biological systems to control pests such as phytonematodes, using strategies and rules of "green" chemistry.

Formulations are essential to obtain more sustainable and multifunctional technologies. In this sense, nanotechnology-based tools – i.e. nanocarriers such as metallic nanoparticles, polymeric nanoparticles, nanoemulsions, among others – can carry compounds, extracts, or blenders resulting in a more controlled release and in a lesser amount of material to be used for phytonematodes control.

In this context, the establishment of a quality system is fundamental to obtain natural sources, residues, or blends and their formulations with reproducibility, repeatability, reliability, stability, efficiency resulting in safe food and customer satisfaction. Thus, this strategy will follow quality regulatory mechanisms that aim to increasingly meet the demands of society, the media, and national/international trade, which currently calls for safe food products with a environmental impact.

Another powerful strategy is correlated to Integrated Pest Management (IPM) or Holistic Pest Management (HPM) that can integrate, during the crop development, strategies such as nanotechnology and blends, resulting in a more efficient pest control, also guaranteeing human health and environment protection.

1.2 Plant Extracts

Plant biodiversity represents an ample source of biologically active materials that could be exploited in crop protection vs a wide range of pests and pathogens, including phytonematodes (Caboni & Ntalli, 2014; Sivasubramaniam et al., 2020; Tiku, 2020). These active materials, denominated extracts, are obtained from plant parts such as barks, leaves, roots, flowers, fruits, seeds, cloves, rhizomes, stems, and others. Plant extracts derived from distinct botanical families have been used as a basis for the development of biopesticides. In this sense, Brazil 6 distinct Biomes (Amazon, Atlantic forest, High Savannah, Semi-arid, Prairie and Wetlands) represent a vast reservoir of plants and, ultimately, extracts and compounds, with a repertoire of distinct biopesticides (Guerra et al., 2020).

When compared with conventional synthetic pesticides, biopesticides are normally less toxic. They usually affect only the targeted pest and closely related organisms, are often effective in relatively small amounts and decompose faster, resulting in a reduced exposure. In general, plant extracts demonstrate a significant risk reduction among pest species as concerns the development of resistance mechanisms, due to a reduced selection pressure. In addition, a remarkable reduction of pest management costs has also been observed, induced by lower infestation pressure, lower accumulated residues and damage, with improved crop protection and yields. Moreover, higher crop protection standards can be achieved based on the application of plant extracts resulting from the positive interactions between botanical products and beneficial macro and microorganisms, in greenhouse and field crops. A lesser toxicological and ecotoxicological risk is also observed for field workers, consumers, wildlife, and the environment. Plant extracts also allow a permanent establishment of beneficial microorganisms, in greenhouse as in field crops.

Finally, they promote an agro-ecosystem that stimulates the establishment and growth of beneficial microorganisms, associated with the crop and soil environment.

On the other hand, some limitations may be related to the use of botanical pesticides. In this sense, the quality of the raw material used for production is crucial to obtain promising results, as the plant material used for production should be selected at the proper time (seasonality). Moreover, the active ingredients of the various plant parts exhibit a huge variability in different geographic areas, limiting the product standardization. Another concern is related to the fact that the majority of botanical pesticides display fast degradation and consequently demand higher application rates and frequency. In addition, regulatory authorization for botanical extracts is expensive and time-consuming, and it is still based, mainly, on the chemical pesticide approval model. The limitation in the production of plant material with nematotoxic effects on a large scale represents another critical issue. Poor economic feasibility for many products obtained from complex and expensive processes, especially when the effective molecules have low solubility, exemplifies a further drawback.

Various plant extracts and toxic substances have been evaluated for phytonematodes control (Oka, 2010). Among them, extracts from plants belonging to the following botanical families stand out: Brassicaceae (*Brassica carinata* and *B. napa*), Fabaceae (velvet bean, *Mucuna* spp. and sunn hemp, *Crotalaria juncea*), Asteraceae (marigold, *Tagetes* spp.), and Euphorbiaceae (castor bean, *Ricinus communis*) (Wang et al., 2002; Hooks et al., 2010; Mokrini et al., 2010; Umar et al., 2010). The common bioactive compounds in botanical pesticides are mostly secondary metabolites, such as steroids, alkaloids, tannins, terpenes, phenols, and flavonoids among others.

In vitro bioassay with aqueous leaf extracts from Bael (*Aegle marmelos*) and Neem (*Azadirachta indica*), at a concentration of 88.53% and 80.31%, exhibited mortality toward the rice root-knot nematode *M. graminicola*, ranging from 80 to 88%, after 48 h exposure (Dongre & Sobita, 2013). In greenhouse experiments, the extracts from Bael and Neem also exhibited a high reduction of root gall (35.33 and 22.66) induced by *M. graminicola* in rice, when compared to the control treatment (nematode alone).

Another study conducted by Ntalli et al. (2020b) *in vitro* showed significant nematicidal activity of aqueous extracts from leaves and wooden stems of *Stevia rebaudiana* (fam. Asteraceae) vs *M. incognita* and *M. javanica*. In addition, *in vivo* bioassays conducted in greenhouse conditions showed substantial efficacy of the leaf powder (95% at 1 g/kg) followed by stems.

Rocha et al. (2017) reported that the aqueous extract (1 mg/mL), the external dialysate (0.5 mg/mL) as well as some compounds (0.01 mg/mL) isolated from *Canavalia ensiformis* seeds exhibited, in *in vitro* conditions, a nematicidal >85% mortality effect on *M. incognita*. It is worth mentioning that the external dialysate showed thermostability, low toxicity against bovine red blood cells, and did not affect non-targeted organisms at the same concentration that killed the nematodes. Under greenhouse conditions, the external dialysate decreased the *M. incognita* egg masses by 82.5% in tomato plants.

According to Ismail et al. (2020), evaluation through *in vitro* bioassay of nematicidal effects, using the aqueous extracts of *Allium sativum*, *Urtica dioica*, *Sophora mollis*, *Ephedra intermedia*, and *Tanacetum baltistanicum* against *M. incognita,* revealed a mortality of 75–95% at concentrations of 0.125–1.0%, after 72 h exposure. Furthermore, methanolic extracts from the aerial part of *Datura stramonium,* and seeds of *Solanum nigrum*, showed nematicidal activity against *M. incognita* and *M. javanica* (Oplos et al., 2018).

Some compounds from plant extracts have also shown effects against phytonematodes. Studies conducted by Aoudia et al. (2012) using the phenolic compounds p-coumaric acid and p-hydroxybenzoic acid, present in the aqueous extract of the *Melia azedarach* fruit pulp, showed *in vitro* a nematicidal effect ($EC_{50/48h}$ = 840 and 871 μg/mL) against *M. incognita*.

The effect of 49 phenolic compounds on *M. incognita,* under *in vitro* and greenhouse conditions, has been evaluated by Oliveira et al. (2019). D-(-)-4-hydroxyphenylglycine, t-butylhydroquinone, L-3-(3,4)-dihydroxyphenylalanine, sesamol, 2,4-dihydroxyacetophenone and p-anisaldehyde were the most effective with (LC_{50}: 365, 352, 251, 218, 210, and 85 μg/mL, respectively) under *in vitro* conditions. Additionally, it was also shown that hydroquinone (at 3.5 mg/plant) reduced *M. incognita* populations and galls by up to 99%, levels similar to the nematicide Carbofuran (at 1.2 mg/plant).

Plant extracts can be used as sources for the “green synthesis” of nanoparticles to control phytopathogens (Kalaiselvi et al., 2017; Abbassy et al., 2017; Silva & Bonatto, 2019; Hernández-Díaz et al., 2020). Green synthesis uses relatively non-toxic, biodegradable, and low-cost chemicals as primary sources to synthesize nanomaterials. Biological resources (plants, microorganisms, various agricultural by-products, among others) can be used from a biological organism or part of it (organs, tissues, cells, biomolecules or, metabolites) as potential sources for the green synthesis of metallic nanoparticles (Sharma et al., 2009; Silva et al., 2015; Lee et al., 2020). Some eco-friendly nanomaterials have potential to control phytonematodes. Aqueous extracts from two tropical plants, *Curcuma longa* (fresh tubers) and *A. indica* (fresh leaves), were used for the green synthesis of silver nanoparticles (AgNPs) that showed dose-dependent toxicity against *M. incognita* (Kalaiselvi et al., 2017). The lethal concentration (LC_{50}) after 72 h of AgNPs for *A. indica* was 6.22 mg/L, and for *C. longa* at 0.54 mg/L. Comparison of these two green synthesized AgNPs, showed a higher mortality rate of the *C. longa* extract synthesized AgNPs (Kalaiselvi et al., 2017). Another example are the extracts of *Conyza dioscoridis*, that showed nanoformulations more toxic than the crude extract vs *M. incognita* (Abbassy et al., 2017).

Botanical pesticides contain bioactive compounds that exhibit different modes of action against phytonematodes. These modes of action, related to the majority of plant-derived bioactive compounds, are complex and little known. The extracts can act as attractants and repellents, or as nematicidal/inhibitory agents, defense elicitors, hatching stimulants/inhibitors, agents of proteins denaturation, and other effects, depending on the type of botanical compound and pest (Sikder & Vestergård, 2020). In this context, nematicidal properties, such as the inhibition of egg hatching and the suppression of nematode populations, are commonly found in botanical pesticides. Some of them can also affect the population of other microorganisms in soil, which further affect the survival of the nematode eggs and juveniles (Khan et al., 2008). Moreover, some compounds can also kill second-stage juveniles (J2), reduce egg masses and galling and/or affect the phytonematode population in its ecosystem (Kepenekci et al., 2016).

For instance, plant extracts obtained from *B. napus*, *L. camara*, *T. erecta,* and *A. indica* can inhibit eggs hatching of *M. incognita*, leading to immobilization and ultimately J2 death. The complex mechanism related to inhibition of root-knot nematodes egg hatching, motility and J2 mortality may be associated with the presence of plant alkaloids, tannins, and glycosides (Akyazi, 2014).

Moreover, a considerable number of phytochemicals found in botanical extracts exhibit a lipophilic property allowing them to straightforwardly dissolve the nematodes cytoplasmic membrane, thus interfering with protein structures accountable for nematode growth, development and survival (Pavaraj et al., 2012).

Paradoxically, despite the massive amount of research and scientific publications demonstrating the effectiveness of botanical extracts, fractions and compounds in phytonematodes control, they have not been translated yet into commercial products. So far, only a few products exhibiting nematicidal activity based on plant extracts have been made available on the world market. They are based on neem (*A. indica*) and garlic extracts (*Allium sativum*). The reasons concerning this problem are related to severe barriers that include: (i) difficulties in scaling-up production of plant materials; (ii) standardization of extracts exhibiting high chemical complexity; (iii) regulatory barriers to commercialization; (iv) slow action of various botanical materials; (v) limited residual action; (vi) accessibility of competing products (Khater, 2012). In addition to this scenario, it is noteworthy to mention that there are still a considerable number of plant species not yet explored around the world, especially in the Brazilian biomes.

1.3 Essential Oil

The essential oil (EO) is the product obtained from a vegetable raw material, usually by steam distillation or mechanical extraction processes. EOs are formed by a mixture of volatile compounds responsible for the characteristic aroma of certain plants, found in glandular brushes, papillae, or in secretory cells and intercellular channels, or present as fluid droplets in leaves, stems, bark, flowers, roots and/or fruits. These lipophilic components commonly found in EOs include terpenes, sesquiterpenes, phenolic compounds, ketones, acids and esters, products of plant secondary metabolism (Figueiredo et al., 2008; Koul et al., 2008; Butnariu & Sarac, 2018). Several studies indicate that the terpenes and phenolic compounds present in EOs are the mostly responsible for plants defense from phytopathogens (Bakkali et al., 2008).

In general, EOs are not toxic to mammals, birds, fish at low concentrations and are not harmful to the environment. Formulations based on EOs are one of the best alternatives to the use of synthetic chemicals for nematode control, especially those that use emulsions or encapsulation, because of prolonged and improved nematicidal efficacy at the field level. In these conditions the EOs are protected from rapid degradation and evaporation from soil, thus allowing a prolonged effect on nematodes (Figueiredo et al., 2008; Laquale et al., 2018).

In addition, it is worth mentioning the expectation of using these products in small areas, in organic productions and mainly in the cultivation of vegetables, where many of the species produced have extremely short planting-to-harvest cycles, and are consumed "*in natura*", thus reducing the risk of chemical residues in harvested products.

The commercial use of products based on EOs requires the availability of sufficient amounts of plant material for continued production and the standardization of final products. The EOs composition may in fact present great qualitative and quantitative variations, in relation to different agronomic factors, plant species, and extraction techniques (Laquale et al., 2015). Furthermore, the high volatility of EOs may result in a low permanence time in soil, and an ineffective action in field conditions. The use of emulsions or encapsulations in formulations aim at reducing or solving these challenges, improving solubility and promoting the EO controlled release. Thus, products used outdoors may require frequent re-applications or adequate protection and release strategies in field situations, which can increase production costs (Koul et al., 2008; Domingues & Santos, 2019).

Research related to the EO effects on phytonematodes has shown promising results. EOs from *Mentha* spp., *Eucalyptus* spp., *Cymbopogon* spp., *Pelargonium graveolens*, and *Ocimum basilicum* demonstrated high toxicity to root-knot nematodes. Jardim et al. (2020) tested the effect of EO from garlic (*A. sativum*) obtained by hydrodistillation in the control of *M. incognita in vitro* and in greenhouse. This EO was more active at 63 μg/mL against *M. incognita* eggs and J2 than the nematicide Carbofuran at 173 μg/mL. Infectivity and reproduction of *M. incognita* in tomato plants cultivated in substrate inoculated with nematode eggs and treated with 0.2 mL/L of substrate were statistically equal to those observed with 0.25 g of dazomet/L of substrate. These results confirm the activity of the garlic EO and its components against *M. incognita*, suggesting its potential as a new fumigant nematicide.

Kalaiselvi et al. (2019) evaluated *in vitro* and greenhouse the nematicidal activity against *M. incognita* of the EOs obtained from *Artemisia nilagirica* grown at different altitudes. EOs obtained from high and low altitudes showed a significant difference in the nematicidal activity, with a lethal concentration (LC_{50}/48 h) of 5.75 and 10.23 μg/mL, respectively. The EOs of *A. nilagirica* reduced the infection of tomato roots by *M. incognita* and significantly promoted the growth of plants in the greenhouse.

EOs from *Monarda didyma* and *M. fistulosa* and their main compounds: carvacrol, γ-terpinene, o-cymene, and thymol, were evaluated *in vitro* and greenhouse for their activity against *M. incognita* and *Pratylenchus vulnus* (Laquale et al., 2018). Both EOs were strongly active against J2 of *M. incognita*, as only 1.0 μL/mL of LC_{50} was obtained after a 24 h exposure to both EOs, while a lower activity was recorded in *P. vulnus* (15.7 and 12.5 μL/mL of LC_{50} for *M. didyma* and *M. fistulosa*, respectively). The almost similar chemical composition of the two tested EOs suggests that their different behavior to the two nematode species could not be only attributed to EOs chemical composition, as variability intrinsic to the nematode species should be also considered (Laquale et al., 2018).

Laquale et al. (2015) evaluated the EOs of *Eucalyptus citriodora*, *E. globulus*, *Mentha piperita*, *Pelargonium asperum*, and *Ruta graveolens* against *M. incognita* on potted tomato in the greenhouse, at a concentration of 50, 100, and 200 μL/kg soil for each EO. At 50 μL/kg, the number of galls and *M. incognita* eggs on tomato roots were significantly lower than the non-treated control, but only in soil fumigated with the EOs from *E. globulus* and *P. asperum*.

The EOs mechanism of action against nematodes is still unclear and it is likely correlated with the chemical structure of its components (Laquale et al., 2015). The presence of volatile monoterpenes and other lipophilic phytochemicals provides an important defense strategy against nematodes. Some EOs lipophilic phytochemicals can easily dissolve the nematode cytoplasmic membrane and directly interfere in the synthesis of proteins underpinning its growth, development, and survival (Lengai et al., 2020). Different hypotheses have been proposed for the mechanism of action on nematodes in the literature, including a neurotoxic mode of action, disruption and change of permeability of nematode cell membranes or the inhibition of AChE (acetylcholinesterase) activity. Further studies are needed to clarify this question (Kostyukovsky et al., 2002; Andrés et al., 2012; Laquale et al., 2018; Saroj et al., 2020; Oka et al., 2000).

Despite the increase in research work and scientific publications on EOs nematicidal properties, few studies have been conducted in the field, and nematicidal products based on EOs are not available on the world market. This fact may be due to difficulties in standardizing products and field applications, regulatory barriers to commercialization, as well as production costs higher than common marketed products available.

Given the global context of sustainable agriculture, the prospect of using commercial nematicides based on EO must overcome these challenges, with more in-depth research in the field, dosage studies, feasibility, use of new application technologies and product standardization. In addition, given Brazil extensive biodiversity, few species of native plants have yet been the subject of research involving EOs in this country.

1.4 Fungal Extracts

Fungi are very promising sources of natural compounds for pest control, for promotion of plant growth, and/or to induce disease resistance (Bills & Gloer, 2016; Bogner et al., 2017; Masi et al., 2018; Keswani et al., 2019; Vinale & Sivasithamparam, 2020). Biopesticides can be obtained from living fungi, their extracts (e.g. exudates, mycelium) as well as their isolated volatile and non-volatile compounds (Degenkolb & Vilcinskas, 2016; de Souza et al., 2018).

Fungi and fungal products are used by several companies for the large-scale production of metabolites, proteins, enzymes, and other compounds. The metabolite-producing fungi with biocidal action can be used as bio-factories and have several advantages such as (i) rapid growth (factor dependent on selected species/lineages); (ii) production of more homogeneous chemical compounds (controlled culture conditions); (iii) production in bioreactors (scaling); and iv) contribution to the bioeconomy (use of agro-industrial residues for the cultivation of some groups of fungi as ascomycetes and basidiomycetes) (Lin & Sung, 2006; Silva et al., 2016). However, the cultivation of fungi has some disadvantages such as: (i) genetic stability maintenance; (ii) homogeneous biological material maintenance; and (iii) contamination during production. Thus, some strategies can be used to solve or significantly minimize these challenges, including (i) methodologies for the fungi storage and tests to verify the genetic stability quality; (ii) protocols for the growth/development of the fungus (nutrients/substrates, pH, temperature, luminosity, among others); and (iii) processes using aseptic conditions.

Metabolite compositions can be altered by some factors such as: (i) species or lineages selection; (ii) biological source selection (e.g. exudates, mycelia) and growth phase; (iii) cultivation conditions (type of substrate/nutrients, pH, temperature, among others); (iv) abiotic (temperature, light, water stress, among others) or biotic stressors (fungi, bacteria); and (v) extraction process and solvents used (Calvo et al., 2002; VanderMolen et al., 2013; Jiaojiao et al., 2018; Khan et al., 2020). Most fungal extracts or metabolites are obtained using reagents such as ethyl acetate and methanol. In this case, these toxic reagents are normally used in both the extraction process and the solubilization step. Strategies to minimize or resolve this negative impact could be (i) to solubilize the extracts obtained in formulations used in sustainable agriculture; and (ii) rely on less toxic or aqueous reagents in the extraction process. In addition, an important point is the characterization of the physical-compound properties (solubility, stability, among others) of extracts or compounds that can lead to formulations that do not impact the environment, as well as animals and humans health. In addition, these formulations also aim to maintain the natural product (extract, or compounds) stability, if subjected to highly variable environmental conditions (rainfall, light intensity, pH, presence of other organisms) allowing its use in different regions, or period of the year.

Theuse of fungi to obtain metabolites is thus a promising strategy for the production of natural compounds under conditions of scalability and reproducibility, for pest control. In this sense, fungi are sources of metabolites active against nematodes, such as terpenoids, alkaloids, peptides, and aliphatic compounds among others (Li et al., 2007; Nisa et al., 2015; Bogner et al., 2017).

Trichoderma species present metabolites with several biocidal applications such as glisoprenin, gliotoxin, gliovirin, viridian, hepteledic acid, polyketides, harzialactones, trichoderm amides and derivatives of α-amino acids. Fungal filtrates of 329 *Trichoderma* strains showed that 15 presented nematicidal activity against *Panagrellus redivivus*, and 14 strains exerted control over *Caenorhabditis elegans*

(Yang et al., 2010). The trichodermin compound was identified in a strain (YMF1.02647) that significantly controlled both species (Yang et al., 2010). Volatile organic compound (6-pentyl-2H-pyran-2-one) of *Trichoderma* sp. (YMF 1.00416) showed nematicidal activity against *P. redivivus*, *C. elegans*, and *Bursaphelenchus xylophilus* (Yang et al., 2012). The extract from *Trichoderma viridae* (200 mg/mL) showed a significant control against both juveniles and egg-hatching inhibition of *M. incognita* (Khan et al., 2020). In this case, the activity was dependent on the growth media as a greater control was observed in the samples obtained from liquid and solid wheat media.

Some metabolites can be produced both by plants and some fungi, such as gibberellins and diterpenoid plant hormones (Bömke & Tudzynski, 2009; Bills & Gloer, 2016). The endophytic fungus *Fusarium oxysporum* 162 showed a promising control activity against *M. incognita* (Hallmann & Sikora, 1996; Bogner et al., 2017). Thus, 11 compounds isolated from *F. oxysporum* 162 extract were analyzed against the root-knot nematode (Bogner et al., 2017). The compound 4-hydroxybenzoic showed the best activity (LC_{50} 104 μg/mL) followed by indole-3-acetic acid (IAA) (LC_{50} 117 μg/mL), and gibepyrone D (LC_{50} 134 μg/mL). The positive controls carbofuran and aldicarb showed LC_{50} 72 h values 64 and 180 μg/mL, respectively. However, the activity of 4-hydroxybenzoic acid was stronger than that of aldicarb. The authors suggested that this fungus can induce resistance against the nematode through two mechanisms: (i) indirect, through increased plant defense by the endophyte-produced 4-hydroxybenzoic acid and indole-3-acetic acid (IAA); and (ii) direct, through the phytohormone (IAA) and the salicylic acid isomer (hydroxybenzoic acid isomers) that could have a dual function, and in the presence of other metabolites produced by the fungus result in the death of *M. incognita* (Bogner et al., 2017).

Basidiomycetes (commonly called mushrooms) are also sources of metabolites with antifungal, antibacterial, antiviral, anti-larvae (larvicidal for mosquito), and nematicidal activities (Sivanandhan et al., 2017). The genus *Pleurotus* is known to have promising species for nematode control (Sivanandhan et al., 2017; Sufiate et al., 2017). An example is observed using *P. eryngii*, as the fungus and its extract reduced the number of intact *Panagrellus* sp. larvae by 60% and 90%, after 24 h treatment, respectively (Sufiate et al., 2017). The authors, however, did not relate this effect to an enzymatic activity, rather to the presence of other metabolites. In this same work, the extract of *P. eryngii* reduced the number of intact eggs of *M. javanica* eggs by approximately 53%, likely through an enzymatic action. Chitinases and proteases activity can affect the structure and development of eggs, causing eggshell ruptures, early hatching, and vacuole formation in eggs and juveniles (Khan et al., 2004; Sufiate et al., 2017).

Fungus extracts can be used for the green synthesis of nanoparticles (Silva et al., 2015; Molnár et al., 2018; Barbosa et al., 2019). Aqueous extracts from *Duddingtonia flagrans* were used as a source for the synthesis of silver nanoparticles (Barbosa et al., 2019). The AgNPs showed action against the larvae of *Ancylostoma caninum* (parasitic nematode infections) indicating a promising action of fungal extracts as sources for synthesis of AgNPs with nematicidal effects.

Obtaining commercial products based on fungi extracts is an opportunity to be explored as these organisms can be used as biofactories for the production of homogeneous compounds as well as for production up-scaling. Another important control strategy is the use of fungi associated with extracts or other types of biological materials. In this case, the blends can be formulated using technology strategies such as hydrogels or nanoformulations, for the controlled release and sustainment of natural nematocides. Brazil has a significant fungi diversity that can be used as an important sourcing strategy for phytonematodes control.

1.5 Sustainable Management: Use of Cover Crops and Plant Residues

In Brazil, cover plants, as well as organic and industrial residues, have been used in the management of different nematode species, the control of which is of economic importance. It is worth to note that their efficiency in nematodes management depends on several factors such as (a) the size of the area; (b) type of culture; (c) species of cover or antagonistic plants; (d) nematode species and population densities; (e) soil type and degradation; and (f) integrated application of other management practices. In this sense, the demand for this type of nematode management by farmers is more and more focused on advantages provided in management (for example greater nematode tolerance of plants, increased vigor and higher yields) as well as costs reduction in sustainable productions.

Cover crops and plant residues are being increasingly used in agricultural systems. Uses have several advantages: recycling nutrients and energy, as well as improving soil physical-chemical conditions for plant growth, and development of microorganisms. Additional benefits of cover crops include nutrients sequesteration (especially nitrates) avoiding their leaching below the crop root zone, suppressing weeds, breaking pest cycles, and providing habitats for beneficial insects and other organisms. Besides these alternatives, cover crops have also been shown to suppress several plant pests including phytonematodes.

On the other hand, cover crops used in phytonematodes control have some disadvantages, such as occupying field crop areas, additional planting costs, agronomical limitations, difficult management, functioning as a weed after the cultivation, and multiplying non-targeted phytopathogens. Concerning the use of industrial residues, plants also can be limited by seasonality, as concerns the production of biomasses and the difficulty of large-scale production.

Some antagonistic plants have been used successfully as cover crops in the control of phytonematodes including *Crotalaria* spp. (*C. spectabilis*), *C. juncea* L., marigold (*T. patula*, *T. minuta*, *T. erecta*) and mucuna, *M. aterrima* (Wang et al., 2007; Claudius-Cole et al., 2015). It is worth mentioning that the black mucuna, *M. aterrima* has proven efficacy vs *M. incognita*, but does not affect *M. javanica* (Miamoto et al., 2016). For the control of *Pratylenchus* spp., the options are more limited. In this case, only *C. spectabilis*, *C. ochroleuca*, and marigold are indicated (Pudasaini et al., 2006; Cruz et al., 2020).

In general, the antagonist plants allow the nematode invasion but prevent their development to maturity. Histopathological analysis of *C. spectabilis* and *C. juncea* roots, infected by *M. javanica*, demonstrated that the nematode induced formation of giant cells in both hosts. However, it was observed that the giant cells were smaller and in fewer numbers when compared to tomato roots, showing that these species are less efficient in meeting the nutritional needs of root-knot nematodes, as compared to susceptible tomato (Silva et al., 1990).

Another factor to be taken into consideration is that *Crotalaria* spp. produces toxic substances, such as monocrotaline, which inhibit the J2 motility in soil. Moreover, the green mass resulting from this plant must be incorporated into the soil, up to approximately 80 days after sowing, before flowering. This procedure is important in avoiding seed production, as well as the high-volume formation of fibrous materials, thus reducing herbicide expenses.

Another efficient strategy is the use of cover crops with non-host plants, that keeps the soil moist for a longer time during the autumn-through-winter period. As a consequence, infective stages of phytonematodes remain active. However, because they do not find roots of susceptible plants to inhabit, they end up consuming their own nutritional reserves and dying.

Among these types of cover crops the *Urochloa* species (syn. *Brachiaria* sp.), *U. brizantha*, *U. decumbens*, *U. ruziziensis*, *U. humidicola* and *U. dictyoneura* proved to be non-hosts for *M. javanica* (Brito & Ferraz, 1987; Inomoto et al., 2007) promoting a considerable reduction in the number of galls per root in tomato plants, that were thus successively cultivated. Dias-Arieira et al. (2003) also demonstrated that *U. brizantha* and *U. decumbens*, in addition to different cultivars of *Panicum maximum* ('Colonião', 'Tanzânia' and 'Vencedor'), are potential grasses for rotation in areas infested with *Meloidogyne* spp. Moreover, the intercropping of *Stylosanthes guianensis* with yams attacked by *M. incognita* reduced tuber damage by about 58.3% (Claudius-Cole et al., 2014).

Currently, many types of grass have been reported as hosts of *P. brachyurus*, with a negative impact on the management of phytonematodes and compromising their beneficial aspects as cover plants (Brito & Ferraz, 1987; Dias-Arieira et al., 2003; Inomoto et al., 2007). For example, *U. decumbens*, *U. brizantha*, *U. humidicola*, *U. dyctioneura*, *U. ruziziensis*, and the hybrid 'grass Mulato' (*U. ruziziensis* clone 44–6 × *U. brizantha* CIAT 6292) may increase the population of this phytonematode. It is worth mentioning that, both sorghum (*Sorghum bicolor*) and forage (*S. bicolo*r × *S. sudanense*) are good hosts for *P. brachyurus*. Contrarily, black oats (*Avena strigosa*) are a poor host, while white oats (*Avena sativa*) and yellow oats (*A. byzantina*) are good hosts.

Moreover,, few studies on the host reaction of wild turnip (*R. sativus* L. var. *oleiferus*) to *P. brachyurus* indicated that this crop is a bad host for the nematode. Comparably, millet (*Pennisetum glaucum*) and black oats are poor hosts to *P. brachyurus*. It means that these three plants shelter and feed *P. brachyurus* in their roots, allowing their reproduction, although at low levels.

Brassicaceae residues plant residues have been reported as biofumigants after incorporation into the soil. These materials exhibit biocidal activity due to the presence of glucosinolates that can suppress soil-borne pests and diseases (Kirkegaard et al., 1993, 1998). According to the literature, *Brassica* spp. may drastically reduce the populations of *M. incognita*, *M. javanica*, *H. schachtii*, and *P. neglectus* (Thierfelder & Friedt, 1995; Potter et al., 1998; Monfort et al., 2007).

In the Andean region of Peru, the aerial part of canola (*B. napus*) and mustard (*Sinapis alba*) plants have been used as suppressants for *Meloidogyne* spp. and *Pratylenchus* spp. in potato (*Solanum tuberosum*) crops, as the decomposition of the incorporated material allows the release of substances toxic to nematodes.

Other examples of organic residues are sorghum (*S. bicolor* (L.) (Moench, 2014)), Neem (*A. indica*) (Akhtar, 2000), castor bean cake (Pedroso et al., 2018) and pork beans (*Canavalia ensiformis*) (Rocha et al., 2017). The use of these materials has been explored in organic agriculture and they are recommended for small farmers, including family farming.

The soil incorporation of industrial plant residues as well as straw to control phytonematodes in sustainable management involves quite complex and little-known mechanisms. The compounds produced through the biomass decomposition processes comprise an arsenal that can exhibit nematotoxic activity, induce plant defense mechanisms, as well as favor soil microfauna, increasing the fungi and bacteria populations including, among other organisms, also natural enemies. The combination of these mechanisms can hence kill or paralyze the phytonematodes.

One of the examples of industrial residues that have a well-established action in the control of phytonematodes is called ‘manipueira’. This type of residue from the processing of cassava in flour mills, found in some regions of Brazil, is abundant in macro and micronutrients and, also, in cyanogenic glycosides, mainly linamarin. These compounds, when hydrolyzed, release cyanide gas, toxic to most life-forms, including nematodes. However, the amounts of hydrocyanic acid (HCN) in the ‘manipueira’ can vary with its origin, because there may be differences in cultivated cassava cultivars, storage time and type of processing, among other factors (Fonseca et al., 2018).

It is worth noting that the use of cover plants can increase the organic matter content levels in soil, making it more friable and non-compacted. With the decomposition of green manures the population of nematodes is reduced, probably due to the release of different allelochemical substances. Moreover, some changes in soil physio-chemistry (pH, porosity, organic matter levels, water infiltration rate, moisture retention, macro, and micronutrients levels) may generate an effective suppression of phytonematodes in distinct types of soils and regions worldwide, when treated with organic materials (Oka, 2010).

Taking into account the aforementioned aspects, it is worth to emphasize the relevance of adequate management choices, considering cover plants and the use of biopesticides based on plant residues. These eco-friendly approaches promote not only sustainable nematode control but may also interfere positively in the physio-chemical and microbiological soil characteristics. However, it is noteworthy that, although the management of nematodes with cover plants and plant residues is frequently used and effective, it has been observed that there are few recent scientific works dealing with these potentially promising materials, hindering an adequate measurement of the practical results obtained.

1.6 Animal and Agro-industrial Wastes

Waste can be defined as any useless, undesirable, or disposable material resulting either after use or through a manufacturing process. These materials can be of animal origin, such as manure, feathers, bones; of vegetable origin, as agricultural waste; and of industrial origin, as by-products (Chindo et al., 2012). In this sense, Brazil stands out as being one of the largest producers in the world of agricultural and livestock wastes, available for different uses.

Due to the high content of organic matter, these residues are often recycled in soil to favor agricultural productivity through fertilization. However, many materials are useful in the control of pathogens or phytonematodes. This practice has been increasingly used since it is inserted in the cyclical economic model in which waste management allows the reuse of by-products, as well as contributes to environmental well-being (Ntalli et al., 2020a).

The beneficial effects of incorporating organic matter from waste in phytonematodes control include (i) increased availability of macro and micronutrients in soil; (ii) changes in the physical, chemical, and biological properties of soil; (iii) direct or indirect stimulation of the proliferation of natural enemies and (iv) increase in plant tolerance (Ntalli et al., 2020a; Peiris et al., 2020).

Possible disadvantages include (i) the lack of standardization of recycled materials and/or compounds; (ii) the availability of the quantity of material needed for effective control of phytonematodes, mainly in large-scale use; (iii) accessibility to waste material and transportation to the destination of application; (iv) limitations of the application method; (v) presence of possible microbial contaminants such as fecal coliforms, bacteria (e.g., *Salmonella* and *Escherichia coli*) as well as residues containing heavy metals; (vi) application limited to the amounts allowed by local legislation; and (vii) suitability as to the timing of manure application.

The use of manure is useful in the control of phytonematodes and, for this reason, has been the most studied and used in this context. The residues can be derived from livestock (bovine, equine, caprine, swine), poultry (chicken, turkey), and fish. The use of these manures can cause direct and indirect effects on phytonematodes, depending on local characteristics, such as soil and crop types, as well as local microbiota.

In Brazil, the use of animal waste to control agricultural pests is an age-old practice used mainly by small producers. The country geographical and climatic conditions, favorable to both agriculture and livestock, offer ideal conditions for the practice to be increasingly applied. Currently, the growing appreciation of agricultural production, with a reduction in the use of synthetic agrochemicals has driven both research and producers to use alternative strategies that are efficient for pest control, especially phytonematodes, for which the use of animal waste has been one of the most common control applications. However, there are still few studies that address in-depth the properties and modes of action involved in this pest control approach.

An example of a direct effect is related to the high nitrogen content and the low C:N ratio provided by manure. In general, the greater availability of N in the residue, mainly in the form of uric acid, the greater the capacity of the organic material to control nematodes (Akhtar & Malik, 2000). This is due to the formation of ammonia as one of the by-products of the organic matter decomposition. The decomposition of materials with high availability of N results in the formation of high concentrations of ammonia in the soil, which are toxic, permeating the cell membranes of phytonematodes, resulting in their inactivation or death (Peiris et al., 2020).

Among the types of animal waste, poultry manure has been the most used and effective in controlling phytonematodes. According to a meta-analysis study, this type of manure provided a 64% reduction in root-knot nematodes, on average, in studies published between 2008–2018 (Peiris et al., 2020). Table 1.1 shows some examples of the action of different types of animal wastes, for phytonematodes control.

Although poultry manure is more effective, in general, some studies also showed beneficial effects in the use of livestock manure (Table 1.1). Such action is generally due to indirect effects, such as the changes in physical, chemical, and biological properties of soil (pH, microflora, and microbiota, for example), as well as the induction of resistance in certain types of crops. Hence, in most cases, the use of animal manure increases productivity and product quality. Although the mode of action is still not very clear, there is strong evidence that the increase in the number of free-living nematodes together with the increase in the population of fungi, bacteria, and nematode predatory mites are responsible for the reduction of phytonematodes.

El-Marzoky et al. (2018) evaluated the use of cow, horse, and turkey manure (30–40 kg/tree), in a Balady mandarin orchard contaminated with *T. semipenetrans*, *Pratylenchus* spp., *Tylenchorhynchus* spp., and *Helicotylenchus* spp. A greater density reduction for the four phytonematodes was observed when turkey (75–78%), horse (64–68%), and cow manure (53–57%) were used, respectively. One of the main factors responsible for this effectiveness appears related to the nitrogen content of the applied residues. According to the authors, the nitrogen content in turkey, horse, and cow dung is about 29,100 ppm, 19,500 ppm, and 17,700 ppm, respectively. For this reason, greater effectiveness in the use of turkey manure was noted, even when it was applied in smaller amounts than in the other treatments.

Other types of waste that have been evaluated for use against phytonematodes are agro-industrial by-products. Among them, some commonly used ones are fruit and cereal peels (Ebrahimi et al., 2016; Maleita et al., 2017; Ali & Zewain, 2018; Izuogu et al., 2019), date palm fibers (Montasser et al., 2016), maize silage (Westphal et al., 2016), brewers spent grain (Thligene et al., 2019); dry-grape marc (Nico et al., 2004), fish waters (El-Deeb et al., 2019), garlic straw (Gong et al., 2013),

Table 1.1 Examples of studies involving animal waste for the control of phytonematodes

Waste types	Rate of application	Phytopathogen	Strategy[a]	Experimental results[b]	References
Cattle dung (compost tea)	100 mL (100%)	*P. zeae*	FE (on maize)	NPR (77.1%)	Izuogu and Usman (2019)
Cattle slurry	48.2 t/ha	*G. rostochiensis*	PE (on potato)	EMR (85.0%)	George et al. (2016)
Cattle slurry	48.2 t/ha	*G. pallida*	PE (on potato)	EMR (82.0%)	George et al. (2016)
Chicken manure	30 kg/tree	*T. semipenetrans*	FE (in fruit orchard)	NPR (68.5%)	El-Metwally et al. (2019)
Chicken manure	3 g/plant	*M. incognita*	GE (on cucurbit)	NGR (61.0%)	El-Deeb et al. (2018)
Chicken manure	40 t/ha	*H. schachtii*	FE (on sugarbeet)	NPR (92.4%)	Nasresfahani (2017)
Chicken manure	30 kg/tree	*Pratylenchus* spp.	FE (in fruit orchard)	NPR (71.4%)	El-Metwally et al. (2019)
Chicken manure	30 kg/tree	*Tylenchorhynchus* spp.	FE (in fruit orchard)	NPR (80.1%)	El-Metwally et al. (2019)
Chicken manure	30 kg/tree	*Hoplolaimus* spp.	FE (in fruit orchard)	NPR (83.0%)	El-Metwally et al. (2019)
Chicken manure	30 kg/tree	*Helicotylenchus* spp.	FE (in fruit orchard)	NPR (61.9%)	El-Metwally et al. (2019)
Chicken manure	3 t/ha	*M. incognita*	PE (on melon)	NPR (87.3%)	Abdel-Dayem et al. (2012)
Chicken manure	2.5 kg/m^2	*Meloidogyne incognita*	FE (on eggplant cv. Baladi)	NPR (81.2%); NGR (63.0%); EMR (70.0%)	Osman et al. (2018)
Cow dung	20 t/ha	*M. incognita*	FE (on sweet potato)	NPR (76.8%)	Osunlola and Fawole (2015)
Cow dung	20 g/kg soil	*M. incognita*	PE (on Ammimajus)	RGR (92.2%); EMR (81.5%); NPR (91.5%)	Zafair et al. (2018)
Cow dung	60 t/ha	*H. schachtii*	FE (on sugar beet plants cv. 005)	NPR (67.9%)	Nasresfahani (2017)
Cow manure	100 kg/ha	*M. incognita*	PE (on okra)	NPR (76.6%)	Tanimola and Akarekor (2014)
Goat dung	20 t/ha	*M. incognita*	FE (on sweet potato)	NPR (82.1%)	Osunlola and Fawole (2015)
Goat manure	3 g/plant	*M. incognita*	GE (on cucurbit)	RGR (56.6%)	El-Deeb et al. (2018)
Goat manure	800 kg/ha	*M. incognita*	GE (on tomato)	RGR (89.0%)	Pakeerathan et al. (2009)

(continued)

Table 1.1 (continued)

Waste types	Rate of application	Phytopathogen	Strategy[a]	Experimental results[b]	References
Goat manure	100 kg/ha	*M. incognita*	PE (on okra)	NPR (67.8%)	Tanimola and Akarekor (2014)
Horse dung	20 t/ha	*M. incognita*	FE (on sweet potato)	NPR (74.6%)	Osunlola and Fawole (2015)
Horse manure (composted)	10 g/kg	*M. incognita*	GE (on tomato)	RGR (4.7%)	Siddiqui and Akhtar (2008)
Pig slurry	24.7 t/ha	*G. Rostochiensis*	PE (on potato)	EMR (77.5%)	George et al. (2016)
Pig slurry	24.7 t/ha	*G. pallida*	PE (on potato)	EMR (75.0%)	George et al. (2016)
Pig manure	100 kg/ha	*M. incognita*	PE (on okra)	NPR (60.0%)	Tanimola and Akarekor (2014)
Poultry dropping (compost tea)	100 mL (100%)	*P. zeae*	FE (on maize)	NPR (86.4%)	Izuogu and Usman (2019)
Poultry dung	20 t/ha	*M. incognita*	FE (on sweet potato)	NPR (87.3)	Osunlola and Fawole (2015)
Poultry manure	100 kg/ha	*M. incognita*	PE (on okra)	NPR (86.7%)	Tanimola and Akarekor (2014)

[a]*FE* field experiment, *GE* greenhouse experiment, *PE* potted experiment
[b]*NPR* Nematode Population Reduction, *RGR* Root Galls Reduction, *EMR* Egg Masses Reduction

onion bulb (Youssef & El-Nagdi, 2010), sawdust (Siddiqui & Akhtar, 2008; Hassan et al., 2010; Faruk, 2019), oil-seed cakes (Pedroso et al., 2018; Faruk, 2019; Pandeya et al., 2019), olive mill waste (Cayuela et al., 2008), rice bran (Hassan et al., 2010; Faruk, 2019) and wine industry by-products (Reiner et al., 2016).

Brazil has several territorials, climatic, and productive advantages that favor the possibility of using agricultural and industrial wastes for pest control. The following passage describes a successful case in the development of control measures against phytonematodes. The liquid residue (100 mL) resulting from the extraction of sisal fibers (*Agave sisalana*) was evaluated against *Radopholus similis* on Grand Naine banana trees under greenhouse conditions. Compared with water-treated plants, the fresh (FR1) and fermented (FR2) residues in concentrations of 25% caused a reduction in the number of juveniles in soil (FR1 = 66% and FR2 = 80%) and in roots (FR1 = 84 and FR2 = 77%). The nematicidal effect of such residues may be associated with secondary metabolites, such as alkaloids, saponins, terpenes, tannins, flavonoids and glycosides. There are reports that the saponins in this type of residue