Nematophagous Fungi: A Biological Agent for Regulation of Plant Parasitic Nematodes

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Abstract— *The occurrence of plant-parasitic nematodes amongst farmers around the globe is a major concern. Farmers also turn to organic pesticides as an additional method to combat pests and diseases. Nematicides are widely available and of significant toxicity in the natural environment, for example, Aldicarb (Temik). Meanwhile, one of the major components of Integrated Pest Management (IPM) is the biological control using other organisms. Many microorganisms predate nematodes, but only handfuls are used for commercial purposes. In addition, the success of a nematode check is strengthened by a combination of two or more biocontrol agents. Fungi can be an efficacious biocontrol agent in particular, and can be feasibly obtained on a large scale. This review would include an outline of the different biomonitoring processes of technological development, but more on the morphological and biochemical dimensions and interactions of nematophagous fungi must be made available. This analysis will contribute to more nematodes and fungal biodiversity resources*.

Keywords— Plant-parasitic nematodes, Biocontrol agent, Integrated pest management (IPM), Nematophagous fungi, Nematicides.

I. INTRODUCTION

The nematodes under the phylum Nematoda (Britannica) are often referred to as roundworms or eelworms. They are the most extensive taxon of the helminth group (Schouteden, De Waele, Panis & Vos, 2015) and all plant and animal groups including aquatic habitats are prone to nematodes (Blouin, Liu, and Berry, 1999). Furthermore, its high fertility rate and reduced lifespan characterize it and survive at varying ambient temperatures, e.g. daily average temperature between < 0 and > 25 ° C, on land and in water. (Moens & Vincx, 2000, p. 2).

Plant-parasitic nematodes are peculiar in terms of feeding behavior by using a stylet to penetrate the feeding host (Jones et al., 2013). The tube known as a stylet begins with the digestive tract. Collagen protein was the precursor to nematode elasticity (Bird and Bird, 1991). Typically, nematodes moult four times during their lifespan before entering an adult stage. In the case of root-knot and cyst nematodes, the most destructive is second-stage juveniles J2 (DACKMAN & JANsson 1991). Besides they are classified into two classes of destructive nematodes, ectoparasite, and endoparasite. Ectoparasitic nematodes feed on the outer layer and cause less damage, while endoparasitic nematodes penetrate the roots and remain destructive for a long time (Agrios, 1997). Other nematodes such as Dagger nematode (*Xiphinema* spp.,) Needle nematode (*Longidorus* spp.,) and stubby-root (*Trichodorus* spp.,) transmit the virus and main mode of ingestion by sucking root sap (Wyss, 1981).

Some plant-parasitic nematodes (PPN) had an impact and ongoing depletion of yield on important agricultural crops. In addition, sedentary endoparasites have a complex structure and are considered to be an important nematode group, e.g. root-node nematodes (*Meloidogyne* spp.) and cyst nematodes (*Globodera* and *heterodera* spp.) (Janson & Lopez-Llorca, 2004). Root-knot nematode (*Meloidogyne* spp) with a huge array of hosts for all communities and the capacity to disperse quickly being the most economically disastrous genera of the plant-parasitic nematode. They are sedentaries and plunge towards the roots for the so-called "root-knot" for nourishment (Elling, 2013). Some root-knot species are *Meloidogyne javanica*, *M.incognita* and *M.arenaria*. Nevertheless, the infestation is probably due to the formation of gall and depletion of water and food. That it would eventually cause the shootings to bolt, wilt, and chlorosis (Crow & Dunn, 2009).

It also poses a serious threat to horticulture crops such as vegetables and cereals and an estimated loss of yield of approximately 50-80 percent (Mukhtar & Kayani, 2019) of nematodes in particular. So far, about one hundred species of nematodes have been recorded. The amount of nematode losses is 20.6 percent in crops reported by Jain et al., 2007 (SHARMA & TRIVEDI).

Heterodera avenae, a cereal cyst nematode called CCN, causes about 15-20% of wheat and 20% of barley due to "Molya" disease (Nicol, Rivoal, Taylor and Zaharieva, 2003). Annual plant-parasitic nematode damages are projected to increase to about $100 billion (Degenkolb & Vilcinskas, 2016).

The most common way in the previous decade of the eradication of Plant-parasitic nematodes by using nematicides. They are inexpensive, and they effectively control nematodes. There are two groups of nematicides, for example, fumigants (1,3 dichloropropene (TeloneII)) and non-fumigants (granules and liquid), e.g. fenamiphos (Nemacur) and aldicarb (Temik). Fumigants became popular because they reduced nematode populations rapidly. (Whitehead, 1986) The predominant toxic compound found in nematicides is Methyl bromide, a multi- purpose fumigant recognized as an ozone-depleting substance (Jansson &Lopez-Llorca, 2004). In addition, nematodes developed resistance to nematicides (Resurgence) and were no longer destroyed by chemical substances (Yang, Tian, Liang, & Zhang 2007). Alternative nematode control measures are less prevalent, such as crop rotation or biological control, an important strategic approach to plant defense (Moosavi & Zare2012). Such problems may be overcome with the use of biological control solutions. This review article focuses on one of these approaches, the nematophagous fungi.

II. NEMATOPHAGOUS FUNGI

Nematodes were found to be a food source that could be parasitized by nematophagous fungi in the 1800s. They are found in fungal taxonomy including Ascomycetes, Basidiomycetes, Zygomycetes, Chytridiomycetes and Oomycetes (Moosavi & Zare, 2012). The majority of fungi live in soil, and their prevalence in organic soils is increased (Janss on & Lopez-Llorca, 2004). The fungi that prey on nematodes are mainly present in nitrogen-deficient soils, including the most available species called nematophagous fungi. Over 150 fungal parasites were taken from cysts and root-knot nematodes. This colonizes the females and attacks *Heterodera glycine* cysts by penetrating the cuticle. *Verticillium chlamydosporium* and *Dactylella oviparasitica* were identified as facultative parasites for attacking cyst and Root-knot nematode young females. *Nematophthora gynophyla* has been found in Northern Europe to be a beneficial Cereal cyst nematode destruction fungus (Kerry,1989).

Some relevant fungal genera include *Trichoderma harzianum*., *Pochonia* Spp., and *Paecilomyces* Spp., which are an excellent monitor of root-knot nematodes (Peiris, Li, Gray, & Xu, 2020). Sharon et al., (2009) have shown that the induction of systemic resistance to *Meloidogyne incognita* by *Trichoderma asperellum* and *Trichoderma harzianum* by virulent genes in tomato cultivars (Pocurull et al., 2020). The combined use of *Pochonia chlamydosporia* and soil residues subsequently decreases the population count of *Meloidogyne javanica* in greenhouse tomatoes (Dalla Pasqua, Dallemole-Giaretta, dos Santos, Reiner, & Lopes, 2020). Trichoderma decreases root-galls and the explanation behind the fact that highly-branched conidiophores and conidia invade various stages of nematodes. Fungi including *Purpureocillium lilacinum,* a filamentous fungi *and Glomus mosseae* have significant potential for handling *Meloidogyne incognita* in cassava and other vegetable cultivation (AKINLESI, 2014). *P. Chlamydosporia* (Horta, 2017) has also encountered potato cyst nematodes, such as *Globodera rostochinensis* and *Globodera pallid* (Nagachandrabose).

Nematodes will inevitably be parasitized, when fungal culture such as *Hirsutella rhossiliensis* and *Drechmeria coniospora* is introduced (Jaffee, Muldoon and Tedford, 1992). Linford (1937), for instance, has found that Meloidogyne in pineapple is suppressed with inoculation in soil by predecious fungal culture.

III. MODE OF ACTION

There are many processes in the tripartite association of nematodes, fungi and roots, including the production of sticky and toxic substances such as Appressoria to infect nematode eggs (Tunlid, Jansson, & Nordbring-Hertz, 1992). The host cells were modified by nematodes secretions and the interface between the plant host and nematodes pathogen was established. The following examples are the adhesive trapping mode in various dimensional networks in the *Arthrobotrys Oligospora* and knobs in *Monacrosporium haptotylum* and branching network in *M.gephyropagon* (Jansson & Lopez-Llorca, 2001). Moozavi & Zare, 2012 illustrated various modifications of fungal infection structures listed in the table below.

TABLE 1
TAXONOMY OF PARASITIC FUNGI AND THEIR INFECTING STRUCTURES

Fungi	Phyllum	Genera	Infecting structures
Nematophagous fungi	Zygomycota	Arthrobotrys	Adhesive hyphae
	Ascomycota	Dactylellina	Adhesive branches Knobs or constricting rings
	Basidiomycota	Nematoctonus	Adhesive knobs
Endoparasitic fungi	Oomycota Chytridiomycota Ascomycota Basidiomycota Blastocladiomycota	Myzoctiopsis Haptoglassa Hirsutella Nematoctonus Cateneria	Zoospores Injecting gun cells Adhesive conidia Spores Zoospores
Egg parasitic fungi	Ascomycota	Paecilomyces	Appressoria
Toxin producing	Basidiomycota	Pleurotus and Coprinus	Pleurotin and Dihydropleurotinic acid, Thorny structure in Coprinus

Source: 'Adapted from Moosavi & Zare, 2012'

Fungal biodiversity and predatory mechanisms rely mainly on environmental factors in soil conditions such as nutrition and temperature (Liu, Xiang, & Che, 2009). Traps are indeed an essential morphological phenomenon and are triggered by artificial means such as peptides, e.g., Phenylalanyl valine or by nematodes (Persmark & Nordbring-Hertz, 1997). The most common form of trapping fungi is sticky branches (e.g. *Arthrobotrys oligospora*, *A.superba*, *Dactylella pseudoclavata*). The tensile strength of the adhesive is a prominent trait of nematode-trapping fungi and increased adhesive secretion after initial contact seems to be necessary for host invasion as seems appropriate for many other host-parasite interactions. The host adhesive is mainly due to the lectin that traps nematode. The random fibrils of the *A.oligospora* are directed in one direction and are perpendicular to the surface of the nematode in their early phases of adhesion (DACKMAN & JANsson, 1991). But due to its nematotoxin, linoleic acid, *Arthrobotrys* Spp., proved damaging (Stadler, Anke & Sterner, 1993). In the genus community, for instance, *Nematoctonus leptosporus* and *N.angustatus* that vary greatly between the trapping Structures on conidia and hyphae illustrate in the following figure 1 and 2.

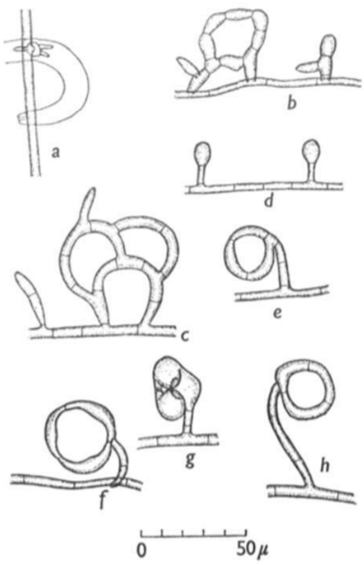

FIG.1.a) Unmodified hyphae with nematode; b) Together, two sticky branches formed a loop; c) adhesive complex or network; d) adhesive knobs or outgrowth; e, f, and g) constricting rings open and closed; h) non-constricting rings

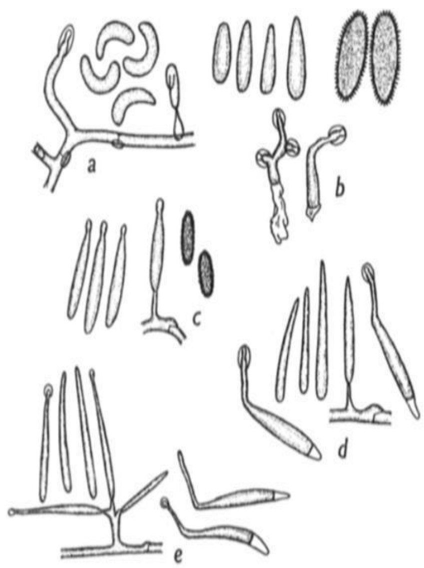

FIG.2. a) conidia and sticky cells of *Nematoctonus campylosporus*; b) chlamydospores, conidia and sticky cells of *N.pachysporus*; c) conidia and chlamydosporus of *N.tylosporus*; d) conidia and adhesive cells of *N.leiosporus*; e) conidia of *N.leptosporus*

Typically, trapping devices originate from mycelium and build on conidia. Unregulated protein (proteases) primarily plays a major role in forming structures such as knobs or constricting rings on hyphae (Andersson et al., 2013). Nematodes are attracted by compounds e.g. CO_2 released from host roots (Green, 1971). At the same time, secondary metabolites such as pleurotin and dihydro-pleurotinic acid formed by *Nematoctonus*spp., (Anke, Stadler, Mayer & Sterner, 1995) have both nematicidal and antimicrobial properties. Food substances are competing and the infection structure can develop and make them parasitic and aggressive (Moosavi and Zare, 2011). Similarly, a certain antagonistic fungus develops spores that grow in the esophagus and digest the nematode (Mankau, 1981).

IV. DISCUSSION

Problems with the Use of Nematophagous Fungi

Besides some nematodes are digested by a fungal parasite, some nematodes can parasitize as well, for example, *Filenchusmisellus* (Du, Xu, Dong, Li, & Wang, 2020). A soil ecosystem cannot suit all parasitic fungi, leading to incomplete colonization and exploitation (Mankau, 1981). Some research shows clearly that fungal inoculum cultureis properly connected with crop planting so as to enhance root colonization, for example, Arbuscular Mycorrhizal Fungi. Biocontrol agents (BCAs) are overlooked due to the high- value markets in developing countries, but farmers are not aware of the use of BCA.

Nevertheless, the virulence and the potential of nematophagous fungi are unclear in many respects, when opposed to nematicides and Tolerant varieties. Therefore, two or more Biocontrol agents and nematophagous fungal strains (Abd-Elgawad, 2016) may be successful for control and combined with other pesticide management strategies, due to their less-skilled existence, which could resolve problems.

V. CONCLUSION

The Biological control of plant-parasitic nematodes is well defined, and we need to be much more informed of their physiological and molecular levels (Jansson & Lopez-Llorca, 2004). Molecular techniques have specifically been developed to examine the characteristics of the nematophagous fungi and their control capacity involving DNA sequences and analysis of markers. This results in a more comprehensive development. Developing commercial products for its effectiveness is therefore significant. Such products also reflect the technical improvements that nematology has made in the progress of biological control technology. Biocontrol products are not extensively used as nematicides, owing to the higher manufacturing costs and the need to establish better control of nematodes on crops. In addition, further research is required to perform field experiments such as seed testing with fungal inoculum and pellet processing of a biological agent, as well as a liquid formulation to check its effectiveness. Farmers gain knowledge of recent technology for better understanding by extension service.

VI. FUTURE PROSPECTS

In the previous study, the majority of nematophagous fungi focused upon the involvement of fungi and nematodes in controlled systems. Although the issue of how to use fungus in biological control has been the driving factor, it is the context. There are top priority questions pertaining to the function of nematodes and nematophagous fungi and signals involved in interactions. In order to understand the biological control capacity of these fungi, input from both field and laboratory investigations should be compiled and incorporated in the future. Biological control of nematodes is a simple and feasible task, but it was indeed an inadequate method for management. Combined prospective efforts will concentrate on current knowledge of fungi and in-depth studies of the following characteristics.

1. Development of detailed but simple methods.
2. Population dynamics studies of both nematodes and fungi.
3. Studies of soil fungi and its survival strategies.
4. Continued work on basic interaction mechanisms.

In some experiments, the nature and the actions of nematodes and nematophagous fungi are already clarified by attracting nematodes to various sources. More thorough studies are expected of the adhesive bind of predatory fungi and endoparasitic spores and the adhesive mechanism in soil. The ability to manipulate nematode attraction behaviors or fungal adhesion processes have provided more ways of designing experiments in a competitive environment to explain the factors influencing the fungi.

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