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An Overview of Biocontrol Strategies for Nematode Management

(*Sirisha T.[1], Firake D M.[2], Madhavan S.[1], Lakshmipathy M.[1], Raju D.V.S.[1] and Ram Pal[1])
[1]ICAR-DFR, Regional Station, Kadiyam, East Godavari, Andhra Pradesh-533125
[2]ICAR-DFR, Zed Corner, Mundhwa Manjri Road, Mundhwa, Pune 411036
*Corresponding Author's email: tadigiri.sirisha3@gmail.com

Plant parasitic nematodes are microscopic organisms that inhabit soil and plant tissues and causes substantial yield losses to major crops throughout the world, including vegetables, fruits, and grain crops. They pose a big threat to food security and plant health, with estimated global yield losses of USD 173 billion annually. Symptoms of PPN (plant-parasitic nematode) damage to crop development are often non-specific and can easily be mistaken for abiotic stress. As a result, PPN infections frequently go untreated, leading to extremely high population densities that are challenging to reduce to an acceptable, non-damaging threshold once established in the field. Chemical control with synthetic nematicides is the most effective strategy to control PPNs, but many of them are banned due to risk to the environment, human health and increased nematode resistance (Zhang *et al.*, 2017). Biocontrol strategy offers alternative approach for plant parasitic nematode management.

Biological control involves utilizing a pathogen or parasite's natural enemies to directly or indirectly inhibit or reduce the incidence or severity of a disease. In case of PPNs, BCAs are capable of suppressing nematodes either by antagonism (being able to parasitize, kill and consume their prey, or by producing molecules that negatively affect nematodes) or by providing plant-growth promoting effects and enhancing plant defuses against PPNs. Several bacterial and fungal BCAs have their potential to suppress most of the PPNs specifically *Meloidogyne spp*., *Heterodera spp* and *Pratylenchus spp.* BCAs have wide array of strategies to target both motile and sedentary PPNs life stages.

Nematophagous fungi

Nematophagous fungi (NF) are capable of capturing, killing and digesting nematodes. Nearly 200 taxonomically diverse species can attack active nematodes. NF are traditionally classified into four groups

1. Nematode-trapping fungi utilize morphological hyphal traps.
2. Endoparasitic fungi use spores.
3. Egg-parasitic fungi target nematode eggs or females.
4. Toxin-producing fungi restrain nematodes before invasion.

Nematode-trapping fungi utilize morphological hyphal traps: Nematode trapping fungi proliferates inside the nematodes body by producing specialized structures for the capture of nematodes in their mycelium. They form structures such as two-dimensional or three-dimensional adhesive nets, adhesive knobs, or constrictor rings, so the fungus can trap nematode and invade inside its body. Hyphae forms a penetration peg when it comes in contact with nematode surface and grows through the interior of the nematode body. Finally, the hyphae project themselves through the exterior of the colonized nematode. Nematode trapping fungus, *Arthrobotrys oligospora* forms a specialized penetration tube to pierce the nematode cuticle and have a significant impact on nematode control in tomato cultivars under greenhouse conditions.

Endoparasitic fungi use spores: Endoparasitic fungi produces spores like conidia or zoospores for infecting nematodes. Mostly they are obligate parasites of nematodes and complete their vegetative stages within the nematode. *Harposporium spp* fungus infects nematode when they ingest their spores by nematode and in case of *Verticillium spp* infect the nematode when their spores are attached on the body.

Egg- and Female Parasitic Fungi: *Pochonia*, *Purpureocillium*, *Trichoderma* and *Lecanicillium* are the most important egg-parasitic fungi. They antagonize phytonematodes mainly by direct parasitism, stimulating plant resistance and promoting its growth. *P. lilacinum* parasitize eggs, young or female nematodes. It secret enzymes like proteases and chitinases to degrade the egg shell and then digest the contents of the egg. Later the fungus spreads inside the egg and entire eggmass filled with hyphae and conidiosphores. Hyphae enters into the nematode cuticle by producing various hydrolytic proteins such as proteases, collagenases and chitinases.They also produce secondary metabolites that are toxic to nematode juveniles. Jatala *et al*., (1979) reported that *P. lilacinus* is capable of infecting female *Meloidogyne* spp. and *Heterodera* spp. and *Globodera* spp. cysts.

Toxic compounds: Few species of Nematophagous fungus produce certain chemical compounds that are toxic to nematodes. These compounds paralyse the nematode and subsequently the fungus consumes them. For an instance, *Pleurotus ostreatus* produces tans-2-decenoic acid that is toxic to nematodes.

Bacterial Bioagents

Bacterial species such as *Agrobacterium* sp, *Arthobacter* sp, *Serratia* sp, *Azospirillum* sp, *Bacillus* sp, *Chromabacterium* sp and *Corynebacterium* sp are reported for the management of plant parasitic nematodes. Mode of action of bacteria on PPNs can be both direct and indirect interaction. Direct antagonistic effects can be achieved via parasitism, colonisation and antibiosis (production of lytic enzymes, antibiotics, toxins, VOC (volatile organic compounds),

Secondary metabolites affect both plant and microbial community. Indirectly, bacteria can enhance host defense mechanisms provoking induced systemic resistance (ISR). Indirect mechanisms include ISR, production of siderephores, hormones, phosphate solubilization, nitrogen fixation, transformation of bacterial microbiome.

Lytic enzymes released by PGPB causes damage to both nematode cuticle and eggs shell which is composed of a protein matrix and chitin layer. Newly isolated strain, *Lysobacter* capsici releases both chitinases and gelatinases which inhibits effectively both second stage juveniles and eggmass of root knot nematode. *Bacillus cereus* (BCM2) strain releases secondary metabolites like 2,4-di-tert-butylphenol and 3,3 dimethyloctane chitosanase, alkaline serine protease, and neutral protease, and induced a 100% mortality in second-stage juveniles of *M. incognita*. Volatile Organic compounds (VOCs) released by *Pseudomonas* and *Serratia* behave as quorum-quenching molecules inhibiting cell-to-cell communication network, leading to a lowered synthesis of virulence and fitness factors such as antibiotics, pigments, exoenzymes, and toxins.

Pasteuria penetrans spores gets attached to the nematode cuticle, penetrate nematode body by germination tube and multiplies endospores inside the body. It affects root knot and cyst females and inhibits the nematode reproduction (eggmass). It also parasitizes the different infected nematode stages and leads to disintegration of nematode cuticle.

Use of biocontrol agents against nematodes offers a sustainable and ecological sound approach to manage nematodes. Continued research and development in this field are crucial for optimising biocontrol strategies and integrating them into holistic pest management programs.

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