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6. Interrelationship Between Nematodes and Root-Nodule Bacteria

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Abstract:

In the intricate world of soil ecology, numerous interactions take place between various organisms, shaping the overall ecosystem dynamics. One such fascinating interrelationship is between nematodes and root-nodule bacteria. Nematodes are tiny, unsegmented worms that inhabit the soil environment, while root-nodule bacteria, also known as rhizobia, are beneficial bacteria that form symbiotic relationships with certain plant species. This *chapter explores the multifaceted interplay between these two crucial components and their effect on crop condition, fertility of the soil, and ecosystem functioning. The interrelationship between nematodes and root-nodule bacteria plays a crucial role in shaping soil ecosystems and influencing plant health and influence each other's populations, behaviors, and functions. Additionally, this paper presents case studies and examples to illustrate the significance of this interplay in agriculture and ecological context.*

***Keywords**:*

Root-nodule bacteria, Rhizosphere, Mutualism, Competition, Antagonism, Plant-microbe interactions

6.1 Introduction:

In the complex tapestry of life beneath the soil's surface, a fascinating interplay between nematodes and root-nodule bacteria quietly unfolds. These microscopic organisms, seemingly inconspicuous, wield an immense power to shape the health and productivity of plants. The symbiotic relationship between nematodes and root-nodule bacteria is a testament to the intricate web of interactions that govern life on our planet (Girgan *et al*., 2020; Jackson *et al*., 2019). Nematodes, also known as roundworms, inhabit virtually every corner of our Earth, from the deepest oceans to the highest mountains. These minuscule creatures, often invisible to the naked eye, play vital roles in soil ecosystems. While some nematodes are free-living, others have evolved specialized relationships with plants, animals, and microbes (Maurya *et al*., 2020; Ilieva-Makulec *et al*., 2016). Among these specialized relationships, the association between nematodes and root-nodule bacteria stands out. Root-nodule bacteria, commonly belonging to the genera *Rhizobium* and *Bradyrhizobium*, are renowned for their ability to form nodules on the roots of legume plants. Inside these nodules, the bacteria convert atmospheric nitrogen into a form that plants can utilize, ultimately enriching the soil (Hodson *et al*., 2019). The interrelationship between nematodes and root-nodule bacteria is a complex dance. Certain nematode species, known as root-knot nematodes (*Meloidogyne* spp.), have evolved to exploit the nitrogen-rich environment within root nodules. These nematodes penetrate the roots of legume plants, causing the formation of characteristic galls or knots. Once inside, they feed on the plant cell contents, disrupting the symbiotic relationship between the plant and the bacteria. Interestingly, not all nematodes are detrimental to the symbiotic association between legume plants and root-nodule bacteria. Some nematodes, such as the bacterivorous nematodes, feed on the bacteria themselves, regulating their populations and potentially aiding the establishment of the symbiosis. This intricate web of interactions creates a delicate balance, where the presence of certain nematodes can either enhance or hinder the efficiency of nitrogen fixation in legume plants (Briar *et al*., 2011). Understanding the interplay between nematodes and root-nodule bacteria is of paramount importance in the fields of agriculture and ecology. The outcomes of this relationship can have far-reaching consequences, impacting plant growth, soil fertility, and ecosystem dynamics. Researchers and scientists strive to unravel the intricacies of this underground dance, seeking ways to mitigate the negative impacts of pathogenic nematodes while harnessing the potential benefits of the symbiosis for sustainable agriculture (Jansen van Rensburg, 2020). Among the various organisms inhabiting the rhizosphere, nematodes stand out as a diverse group of microscopic worms that interact with plants and other soil organisms in multifaceted ways. They are abundant in the rhizosphere due to the presence of root exudates and decaying organic matter, which serve as their primary food sources. Nematodes in the rhizosphere can be broadly categorized into three groups based on their feeding habits: bacterial-feeding, fungal-feeding, and plant-parasitic nematodes. Bacterial-feeding nematodes graze on soil bacteria, regulating their populations and impacting nutrient cycling in the soil (John *et al*., 2019 a). They play a vital role in releasing essential nutrients from microbial biomass back into the soil, making them available for plant uptake. While most nematodes in the rhizosphere are beneficial, some species can be plant-parasitic, causing considerable damage to crops (Maurya *et al*., 2023). These nematodes infect plant roots, disrupt nutrient uptake, and may lead to stunted growth and reduced yields. Interaction between nematodes and root-nodule bacteria form symbiotic relationships with plants, benefiting both parties. For instance, some nematodes engage in mutualistic associations with plants, where they receive nutrients from specialized root structures called "giant cells" while contributing to enhanced nutrient absorption for the host plant. In response to nematode infestations, plants have evolved various defense mechanisms. They can release chemical signals through root exudates, attracting beneficial nematodes or microbes that prey on harmful nematodes, leading to a form of biological control. Root-nodule bacteria, also known as rhizobia, form a fascinating symbiotic relationship with leguminous plants, such as beans, peas, and clovers. This relationship leads to the formation of specialized structures called root nodules on the plant's roots. Within these nodules, the rhizobia fix atmospheric nitrogen into a form that the plant can utilize as a nutrient, while the plant provides the bacteria with a source of carbon and other nutrients. This mutualistic association benefits both the plant and the bacteria, enhancing their growth and development. However, the interactions between root-nodule bacteria and nematodes are more complex. Nematodes are microscopic, worm-like organisms that can either be beneficial or harmful to plants. Some nematodes are free-living and play important roles in soil nutrient cycling, while others are parasitic and can damage plants by feeding on their roots.

Beneficial Interactions: Certain nematodes, known as beneficial or entomopathogenic nematodes, can establish a synergistic relationship with root-nodule bacteria. These nematodes are parasitic to insects and can use the rhizobia-infected root nodules as a site for reproduction and survival. The plant benefits from this interaction as it helps to control insect pests and enhances nutrient uptake from the soil due to the increased nodulation.

Harmful Interactions: Other nematodes are harmful to leguminous plants and can negatively impact the symbiotic relationship between root-nodule bacteria and the plant. These nematodes may feed on the root nodules directly, leading to reduced nitrogen fixation and impaired plant growth. They can also damage the root system, making it less efficient in absorbing nutrients and water from the soil.

To mitigate the negative effects of harmful nematodes, some root-nodule bacteria have evolved mechanisms to protect the nodules from nematode attacks. For instance, some rhizobial strains produce compounds that deter nematodes or inhibit their growth within the nodules. Additionally, the plant's immune response may be triggered, leading to the production of defense compounds that can deter nematode feeding. Researchers continue to study these intricate interactions between root-nodule bacteria and nematodes to gain a deeper understanding of how these relationships impact plant health and growth.

Understanding these interactions can potentially lead to the development of strategies to enhance nitrogen fixation and protect leguminous crops from nematode-induced damage. The interplay between nematodes and root-nodule bacteria is a significant ecological and biological relationship that occurs in the context of plant-microbe interactions. Root-nodule bacteria, commonly known as rhizobia and nematodes are both important components of the soil ecosystem and play crucial roles in nutrient cycling and plant health.

6.2 Role of Legumes and Non-Legumes:

Legume crops, such as soybeans, peas, and alfalfa, have a unique ability to form a symbiotic relationship with root-nodule bacteria, primarily belonging to the genus Rhizobium. This symbiotic association benefits both the plant and the bacteria. The process begins when legume plants release specific compounds called flavonoids into the soil (John *et al*., 2019 b). These flavonoids attract compatible root-nodule bacteria, which then colonize the root hairs of the legume plant (Pant *et al*., 2023). In response, the plant forms specialized structures called root nodules, where the bacteria reside. Within the root nodules, the bacteria convert atmospheric nitrogen into a form that plants can use, a process known as nitrogen fixation. The plant, in turn, provides the bacteria with a source of carbon and other nutrients. This mutualistic relationship results in increased nitrogen availability for the legume crop, reducing the need for synthetic nitrogen fertilizers, and promoting healthier plant growth (Maurya *et al*., 2023 b). Interestingly, the presence of root-nodule bacteria in legume crops can also influence their interactions with nematodes. Some studies suggest that certain strains of root-nodule bacteria possess nematicidal properties, meaning they can inhibit or kill plant-parasitic nematodes. These bacteria produce compounds that are toxic to nematodes or induce systemic resistance in the plant, making it less susceptible to nematode infestation. Furthermore, the presence of root-nodule bacteria can alter the root exudates of legume plants, affecting the behavior and activity of nematodes. These changes can influence nematode attraction, feeding behavior, or population dynamics in the rhizosphere. In contrast to legumes, non-legume crops generally do not form a symbiotic relationship with root-nodule bacteria. However, they can still play a role in the interrelationship with nematodes. Non-legume crops can serve as alternative hosts for plant-parasitic nematodes, providing a reservoir for nematode populations to persist even during crop rotation or fallow periods. According to Bekal *et al*. (2001), members of the genus Pasteuria are obligate, mycelial, endospore-forming bacterial parasites of water fleas and plant-parasitic nematodes. This genus contains a variety of bacterial species that have demonstrated excellent promise as biocontrol agents for plantparasitic nematodes. Pasteuria is a deeply embedded member of the Clostridium-Bacillus-Streptococcus branch of the Gram-positive Eubacteria, according to recent analysis of a section of the 16S rRNA gene (Anderson *et al.,* 1999; Kitagami and Matsuda 2020).

The genome of *P. panetrans* was sequenced, and the results suggested that *P. Penetrans* may have evolved from an ancient symbiotic bacteria partner of nematodes, presumably when the root-knot nematode evolved into a highly specialized plant parasite (Charles *et al*., 2005). So far, four nominal Pasteuria species have been reported. The nematode species that are affected include *P. penetrans,* which usually parasitizes root-knot nematodes like *Meloidogyne* spp., *P. thornei*, which often parasitizes root-lesion nematodes like *Pratylenchus* spp., and *P. nishizawae*, which is found on cyst nematodes of the families Heterodera and Globodera (Kou *et al*., 2020).

Nematophagous bacteria can develop systemic plant resistance, parasitize other species, produce toxins, antibiotics, or enzymes, compete with other creatures for food, and even benefit plants. They cooperate to control nematodes by directly inhibiting them, promoting plant development, and encouraging the colonization and action of microbial antagonists in the rhizosphere. Exclaim for endophytic, symbiotic, and protein-forming bacteria.

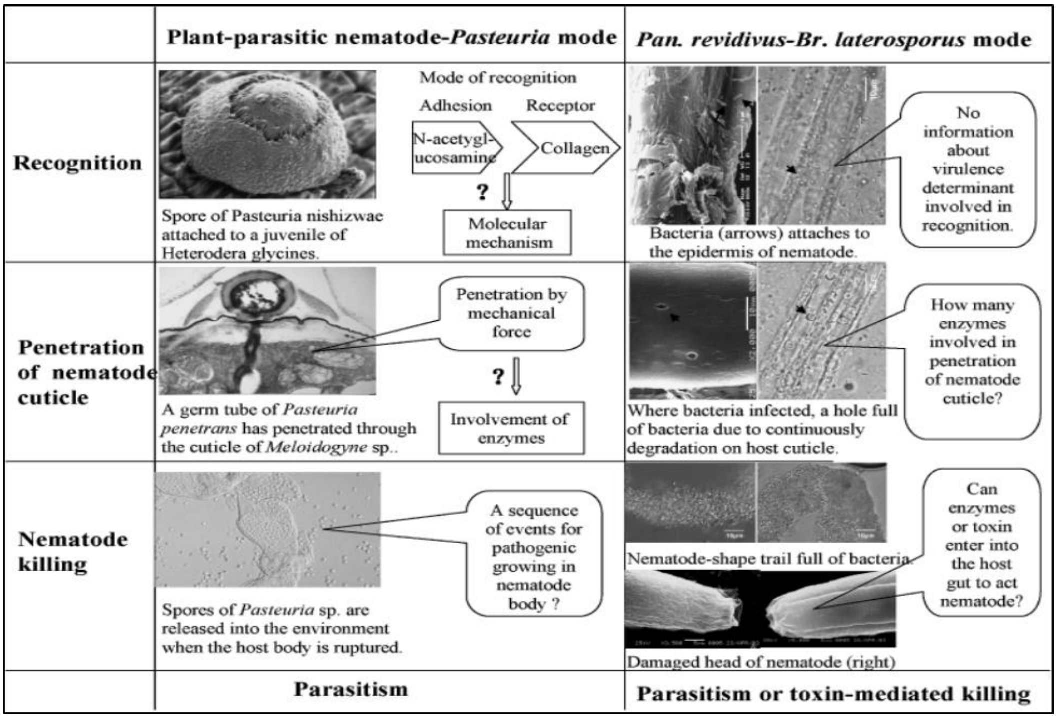

Figure 6.1: Bacterium–Nematode Interaction- Pathogenic Mechanisms of (*M Incognita –P. Penetrans; P. Redivius–B. Laterosporus*) (Tian *Et Al.* 2007).

6.3 Rhizobacteria- Parasitic Bacteria:

In order to biologically control plant-parasitic nematodes, rhizobacteria have also been investigated (Sikora, 2018). One of the most prevalent populations in the rhizosphere that can combat nematodes is composed of aerobic endospore-forming bacteria (AEFB), primarily *Bacillus* spp. and Pseudomonas spp. (Rovira & Sands, 1977; Krebs *et al*., 1998; Pandey *et al.*, 2022 b). Furthermore, several researchers have reported that Bacillus spp. directly oppose species of plant-parasitic nematodes from the genera *Meloidogyne, Heterodera*, and *Rotylenchulus* (Insunza *et al*., 2002; Kokalis- Burelle *et al*., 2002; Meyer, 2003; Giannakou & Prophetou- Athanasiadou, 2004; Li *et al.*, 2005).

In order to biologically control plant-parasitic nematodes, rhizobacteria have also been investigated (Sikora, 2018). One of the most prevalent populations in the rhizosphere that can combat nematodes is composed of aerobic endospore-forming bacteria (AEFB), primarily *Bacillus* spp. and *Pseudomonas* spp. (Krebs *et al.*, 1998). Furthermore, several researchers have reported that *Bacillus* spp. directly oppose species of plant-parasitic nematodes from the genera *Meloidogyne, Heterodera*, and *Rotylenchulus*.

Additionally, when interacting with nematodes, rhizospheric Pseudomonas strains display a variety of harmful pathways (Kerry, 2000; Jayakumar *et al.*, 2002; Andreogloua *et al.*, 2003; Siddiqui *et al.*, 2005). It has been investigated how some Pseudomonas strains control the number of plant-parasitic nematodes. Antibiotic biosynthesis and systemic resistance development are two of these pathways (Siddiqui and Shaukat 2003).

Antagonistic effects shown by other rhizobacteria against nematodes include members of the genera *Corynebacterium, Agrobacterium, Alcaligenes, Phyllobacterium, Aureobacterium, Azotobacter, Beijerinckia, Burkholderia, Actinomycetes, Chromobacterium, Clostridium, Desulforibtio, Comamonas, Enterobacter*, *Curtobacterium, Flavobacterium, Clavibacter, Gluconobacter, Hydrogenophaga, Klebsiella, Methylobacterium, Arthrobacter, Phingobacterium, Rhizobium, Serratia, Stenotrotrophomonas Desulforibtio*and *Variovorax* (Hallmann *et al.*, 2002; Siddiqui & Mahmood 2001; Jonathan *et al*., 2000; Mahdy *et al*., 2001; Insunza *et al.*, 2002; Khan *et al*., 2002; Meyer, 2003). Nematode inhabitants reduced by Rhizobacteria preferably by competing for essential nutrients, regulating nematode behavior, plant–nematode recognition interference, promoting growth of host plant (El-Nagdi & Youssef, 2004 and others). One of the most harmful endoparasitic sedentary nematodes in the world is the root-knot nematode (Trudgill and Blok 2001). This genus's many members share around 5500 different plant types as their primary hosts. *Meloidogyne* species are among the root-knot nematodes that are known to have the widest geographic distribution. They can be found on a variety of plant hosts, including ornamental, fruit trees, weeds, crop and vegetable seeds, and ornamentals (Luc *et al*., 2005). According to Bakr *et al*. (2011), root-knot nematodes are one of the main factors restricting agricultural output in Egypt, and sandy soil, particularly in recently reclaimed regions, had the highest frequency of the root-knot disease caused by *Meloidogyne* spp. One of the most widely cultivated vegetable crops in the world is eggplant (*Solanum melongena* L.). Root knot nematode infestation is reported to cause severe damage to eggplant (Abd-Elgawad 2014). Due to its compatibility with the climate and non-toxic nature, biological control is becoming more widespread (Jiang *et al*., 2014). Utilizing these environmentally friendly microbes contributes to environmental preservation and pollution-free environments. The three categories of bacteria that make up the bacterial antagonists are endophytic, epiphytic, and endoparasitic bacteria. According to Abd-Elgawad (2014), bacteria are controlled biologically by means of parasitism, competition, and antibiosis. According to Lucas *et al.* (2014), bacteria's siderophores can also be used by plants to determine induced systemic resistance (ISR).

According to in vivo investigation, the use of bio-agents (*P. amylolyticus, B. agri, G. frateurii, B. mobilis, A. aloeverae*, and *P. stutzeri* and their mixture) reduced the overall numbers of M. incognita on aubergine in contrast to the nematicides Mocap 15% (Ethoprophos) and Micronema. In comparison to the control treatment, AbdelRazek and Yaseen (2020) found that all treatments had reduced reduction percentages of J2s, galls, females, egg masses, eggs per egg mass, final populations, and nematode accumulation rates. Root lesion nematodes (*Pratylenchus* spp.) are the primary biotic danger to soybean farming mostly in Europe, early maturing cultivars of soybean offer a high yield potential. Growing soybean in low-input rotation systems is encouraged by the very effective *Bradyrhizobium japonicum* inoculants' ability to fix nitrogen in the root nodules. We looked into how *P. penetrans* affected *B. japonicum* ability to fix nitrogen in a density-dependent manner. The quantity and weight of nodules, the density of viable bacteroids in nodules, and nitrogen fixation as determined by the concentration of ureides in leaves were all impacted by less than 130 injected nematodes. The percentage of injected nematodes that penetrated the roots rose as the number of nematodes increased, and the symbiosis' negative impacts intensified, resulting in non-functional nodules at 4,000 and more worms. The growth of nodules, the density of bacteroids, and nitrogen fixation were all impacted by *P. penetrans* invasion of roots with fully developed nodules, although the number of nodules was unaffected. On the other hand, nodulation of already infected roots led to a large number of tiny nodules and reduced bacteroids and nitrogen fixation densities. According to an experiment using split-root systems, *P. penetrans* invaded and damaged the nodules on a local level, but they also dramatically impacted the nodule symbiosis through a plant-mediated mechanism (Elhady *et al*. 2020; Pandey *et al*., 2022 a).

6.4 The Influence of Soil Conditions On Nematode-Root Nodule Bacteria Interactions:

The interactions between nematodes, root nodule bacteria (rhizobia), and plants in the context of soil conditions are complex and play a significant role in shaping plant health, growth, and overall ecosystem dynamics. Nematodes are microscopic roundworms that can be either beneficial or harmful to plants, while root nodule bacteria are primarily known for their ability to form symbiotic relationships with leguminous plants, aiding in nitrogen fixation.

Soil conditions can influence nematode-root nodule bacteria interactions:

- **Soil Texture and Structure:** Soil texture (proportions of sand, silt, and clay) and structure affect water retention, aeration, and nutrient availability. Sandy soils drain quickly, potentially reducing the survival of nematodes and rhizobia due to limited water availability. Compacted soils hinder root growth and restrict nematode movement, affecting their interactions with rhizobia and the plant's overall nutrient uptake.
- **Soil pH:** Soil pH significantly influences both nematodes and rhizobia. Nematode species vary in their pH preferences, with some thriving in acidic soils while others prefer neutral to alkaline conditions. Rhizobia often exhibit specific pH optima for effective nodulation and nitrogen fixation. Altered pH levels can impact the survival of both nematodes and rhizobia, subsequently affecting their interactions with plants.
- **Soil Nutrient Availability:** The availability of essential nutrients like nitrogen, phosphorus, and potassium can influence nematode behavior and plant-rhizobia interactions. High nitrogen levels might favor nematodes that feed on plant roots, leading to reduced root nodulation as nitrogen fixation becomes less critical for the plant.
- **Soil Moisture:** Soil moisture content affects nematode mobility, survival, and reproductive rates. Drought conditions can reduce nematode populations and disrupt their interactions with both plants and rhizobia, potentially impacting plant growth and nodulation.
- **Soil Microbial Communities:** The soil is home to a diverse array of microorganisms, including beneficial and pathogenic nematodes, as well as various rhizobial strains. Interactions between nematodes and rhizobia can be influenced by competition and

predation within the microbial community. Certain nematodes may even feed on rhizobia, impacting their effectiveness in promoting plant growth.

- **Soil Temperature:** Soil temperature affects the metabolic activities of nematodes, rhizobia, and plants. Nematodes are ectothermic organisms, so temperature fluctuations can impact their movement and lifecycle stages. Rhizobia are also influenced by temperature, as it can affect their ability to colonize and nodulate plant roots.
- **Soil Oxygen Levels:** Adequate oxygen availability is crucial for both nematodes and rhizobia. Oxygen deficiency due to waterlogging can negatively impact root health, reduce rhizobial activity, and affect the movement and survival of certain nematode species.
- **Soil Contaminants:** Contaminants such as heavy metals, pesticides, and pollutants can alter nematode populations and affect the viability of rhizobia. These contaminants can disrupt the delicate balance of interactions in the soil ecosystem.

Understanding the intricate relationships between nematodes, root nodule bacteria, and plants within various soil conditions is essential for optimizing plant health and agricultural productivity. Researchers continue to study these interactions to develop sustainable agricultural practices, including crop rotation, cover cropping, and soil amendments, that can influence nematode-root nodule bacteria interactions in ways that benefit plant growth and ecosystem health.

6.5 Conclusion:

Legumes are unique in their response to rhizobial Nod factors and we are only beginning to understand the molecular mechanisms, which govern the development of a nodule during legume-rhizobia symbiotic association. The preceding experiments demonstrate that the Nod factors generated by these beneficial organisms may in some way be similar to signals that are generated by plant parasitic root knot nematodes. The root knot nematode signal molecules appear to share common receptors and induce similar downstream cytoskeletal and morphological changes to those that are generated by bacterial Nod factors. Similar to rhizobial Nod factors the nematode-signals are capable of cellular de-differentiation leading to the formation of a nodule-like structure, the gall. Although similarities between nodules and gall may be limited, the results suggest that horizontal gene transfer may have been a key in the development of nematode parasitism. Future experiments to elucidate the molecular and physiological pathways induced by nematodes, rhizobia and mycorrhiza will play major role in our understanding of these economically important relationships. Currently measures to control plant parasitic nematodes are limited and this results in substantial crop losses. Therefore, identification of processes induced by nematodes will be valuable resources for creating new forms of nematode resistant plants or chemical-control strategies.

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