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Research Review

Management of Plant-Parasitic Nematodes (PPNs) to Protect the Agriculture: A Brief Summary

Sangita Lahiry*[1]

[1] Department of Zoology, Banwarilal Bhalotia College, G. T. Road, Ushagram, Asansol - 713 303, West Bengal

Abstract

Plant-parasitic nematodes (PPNs), which parasitize plants, are a costly burden to crop productivity and pose a serious threat to the security of the world's food supply. Due to their intricate relationships with the host plants, extensive host range, and degree of damage caused by infection, root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Heterodera* and *Globodera* spp.), and lesion nematodes (*Pratylenchus* spp.) rank at the top of the list of the most economically and scientifically important species. The identification of molecular elements involved in nematode parasitism and the distinction between genotypes of susceptible and nematode-resistant plants are now two major applications of genetic sequencing analysis. The dynamic and intricate nature of plant-nematode interactions has been greatly improved by these in-depth analyses. This review focuses on the application and promise of contemporary technologies, including biologicals, botanicals, non-host crops, related rotations, and modern strategies against PPNs in sustainable agro-ecosystems. This paper provides an overview of how they interact with other biotic and abiotic elements from the perspective of PPN management in order to assess their potential for control.

***Key words*:** Plant-parasitic nematodes (PPN), Crop productivity, Nematode-resistant plants, Biological control, PPN management

The coexistence of nematodes and plants over millions of years has led to the emergence of the plant-parasitic nematode. Nematodes are widely dispersed vascular plant diseases that have been linked to significant production losses. An "evolutionary arms race" has resulted from the complex interaction between the plant and the parasitic worm. In order to generate feeding sites, phyto-parasitic nematodes have evolved means of suppressing host immunological reactions. Plants, in turn, have created specialized chemicals that detect pathogens and indicate the initiation of immune responses. Research on non-chemical techniques of nematode control has received a lot of attention as a result of the decline in the usage of chemical pesticides. Recent studies on nematodes have focused on the genetics and molecular patterns linked to plant defense and damage in the event of worm infection [1]. Microbial priming has also been the subject of much research, with great success [2]. In order to completely understand the interaction between PPNs and their host and non-host plants via the elicitor-receptor reciprocal action, several approaches are now being developed [3-4]. The knowledge required to create long-lasting nematode resistance in plants should be provided by these significant mechanisms. Additionally, advantageous microorganisms and synthetic elicitors that can be thoroughly and successfully utilized can activate the systems involved in plant defiance and protection against PPN [4]. The principles of the PPN-plant connection are a major focus of the current study in a number of different areas. However, there have been linked chances to take advantage of the accessible programmes to securely regulate nematodes. As a result, many of the long-lasting crop protection techniques are anticipated to be safe substitutes for chemical nematicides. The general approaches to using secure antagonists of PPNs were recently covered by Abd-Elgawad [5]. They often depend on either biological management for conservation purposes or augmentation (inoculative and inundative). This review updates and expands on the use of such tactics. It emphasizes the possibility and usage of a number of methods and approaches that can support PPN management. These strategies could involve the use of biological control agents (BCAs), botanicals (like antagonistic plants), host plant resistance to nematodes with associated crop rotations, and other cutting-edge therapies. The goal is not only to prevent nematode-caused plant damage and production losses and do our part to support sustainable agricultural ecosystems, but also to summarize recent developments in the study and use of these methods. It also addresses agricultural practices that improve PPN control and highlights important aspects of their effectiveness and wider exploitation, as well as their advantages and disadvantages.

Origin of plant-parasitic nematodes

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Correspondence to: Sangita Lahiry, Department of Zoology, Banwarilal Bhalotia College, G. T. Road, Ushagram, Asansol - 713 303, West Bengal, Tel: +91 8961658098; E-mail: sangita.lahiry@gmail.com

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Why do some worms turn into parasitic plants? Plant parasitism, which has through three different evolutionary cycles as a result of the dynamic relationship between nematodes and their plant hosts, has produced significant advantages for worm survival and growth [6-7]. The pre-"Cambrian explosion" (400 million years before the burst of animal phyla), according to one evolutionary theory, is when these ancient microscopic roundworms first appeared [8]. According to evidence, the first plant-parasitic nematodes likely appeared around 235 BC [9], whereas Needham is credited with describing the first plant-parasitic nematodes after he noticed galling symptoms in wheat [10]. Root-knot nematodes, a kind of plant-parasitic nematodes with agricultural importance, were first discovered by Berkeley, who noticed the development of galls on cucumber roots [11]. The lives of plant-parasitic nematodes vary. While some nematodes feed externally, others just infiltrate the plant cells. Nematodes that are endoparasitic settle inside plant tissue while ectoparasitic nematodes remain outside the host cells and feed on plant roots. The California dagger nematode, or Xiphinema, is an example of an ectoparasitic nematode and carries the Grapevine fanleaf virus. Viral contamination that results has a devastating economic impact on grapes everywhere [12]. The classes of migratory and sedentary endoparasitic nematodes are further separated. Sedentary worms become static after creating a feeding site within the host tissue, in contrast to migratory endoparasitic nematodes that migrate within the root and extract the cytoplasm, killing the host cell [13]. *Pratylenchus* species (a lesion nematode), *Radopholus* species (burrowing worms), and *Hirschmanniella* species (a rice root nematode) are examples of migratory endoparasitic nematodes that are significant economically.

The effect of plant-parasitic nematodes on crops

Nematodes that parasitize plants are an expensive burden in crop production. There are more than 4100 species of worms that parasitize plants [14]. They collectively harm crops to the tune of between $80-118 billion annually [15-16]. The most economically significant nematode species, which account for 15% of all known nematode species, directly target the plant roots of important agricultural crops, preventing water and nutrient intake and lowering agronomic performance, overall quality, and yields. The most significant agricultural pests are thought to be nematodes in the order Tylenchida, which are diseases of plants, invertebrates, and fungi [16]. The most productive species among all the significant plant-parasitic nematodes are the sedentary subgroups that create a long-term feeding site inside the plant host and collect nutrients while they go through their life cycles. Due to a unique and complicated mechanism of host cell transformation that results in the creation of a sustained feeding system, sedentary nematodes have a natural advantage over their migratory counterparts. Surprisingly, just a small percentage of the roughly 4000 plant-parasitic nematodes reported cause major financial losses in crops. *Heterodera, Hoplolaimus, Meloidogyne, Pratylenchus, Rotylenchulus,* and *Xiphinema* were the principal genera of phytoparasitic nematodes reported to cause crop losses [17].

Biological control agents (BCAs)
Their general classification and properties

Currently, bacterial and fungal species are regarded as the most effective and important biocontrol agents (BCAs) against PPNs [18-19]. Others, less well known and less effective BCAs include predaceous nematodes, mites, viruses, protozoans, oligochaetes, collembola, algae, and turbellarians. It is doubtful whether such a large number of BCAs and their bioactive chemicals can consistently limit PPN populations. Many obstacles must be removed in order to verify their efficacy when applied to seeds, cultivated soil, or seedling media for PPN control. These obstacles include their mass culture, formulation, application methods, and interactions. Two main groupings can be made of these BCAs' modes of action: those that directly oppose PPNs and those that indirectly support plant growth regulators. However, PPN control is accomplished via a number of processes that involve BCAs and/or their bioactive metabolites. Recent research on the other major taxon of BCAs revealed the presence of cry protein-forming bacteria, endophytic bacteria, rhizobacteria, obligate parasite bacteria, symbiotic bacteria, and opportunistic parasitic bacteria [5]. Additionally, these BCAs are capable of producing plant growth promoters [20]. They can directly help plants by facilitating resource possession and the generation of active substances and hormones (such as gibberellins and cytokinin) required for plant growth. Indirectly, they can make antibiotics and lytic enzymes to control diseases and pests. Furthermore, these BCAs can prepare plants to withstand PPN. Recent research by Molinari and Leonetti [2] shows that BCAs can interact with roots to prepare plants for infection by *Meloidogyne* spp. root-knot nematodes (RKNs) by upregulating endogenous defense genes. They might include systemic acquired resistance genes like PR-1, PR-1b, PR-3, and PR-5 that are associated to salicylic acid-dependent pathogenesis. Additionally, related enzymes like glucanase and endochitinase demonstrated increased activities in the roots of pre-treated inoculated plants, which may open up new doors for novel PPN management.

Fungal and bacterial biocontrol

Numerous fungi belonging to different genera, including *Trichoderma, Purpureocillium, Catenaria, Actylellina, Dactylellina, Arthrobotrys, Aspergillus, Monacrosporium, Hirsutella,* and *Pochonia,* are excellent BCAs against PPNs, particularly for the control of RKNs [18], [21-22]. For instance, endophytic fungi belonging to the genera *Trichoderma, Fusarium, Alternaria, Purpureocillium,* and *Acremonium* have the ability to colonize plant roots and improve plant defense through a variety of mechanisms [23]. *Purpureocillium lilacinum* (CG1042, CG1101) and *P. chlamydosporia* (CG1006, CG1044) are two of the most promising strains of *P. chlamydosporia* and *Purpureocillium lilacinum* strains that Silva *et al*. [24] screened out of 33 strains. Both *P. lilacinum* and *P. chlamydosporia* resulted in 44 and 34% suppression of *M. enterolobii* eggs on tomato roots, whereas *P. chlamydosporia* recorded 34% suppression of *M. enterolobii* eggs on banana roots. The arbuscular mycorrhizal fungi (AMF), which serve as necessary plant root symbionts, are another class of potential fungus. The plant provides the symbionts with photosynthetic carbon, and the latter help the roots absorb more nutrients and promote root growth and structure. Additionally, they frequently compete with PPNs for nutrients and space and cause plant systemic resistance [25]. In addition, a wide variety of bacterial species from a variety of genera, including *Pseudomonas, Serratia, Bacillus, Pasteuria, Achromobacter, Variovorax, Rhizobium, Agrobacterium, Comamonas, Arthrobacter,* and *Burkholderia,* have demonstrated nematicidal activity against PPNs [26-29].

Nematode-suppressive soils

Suppressive soils were defined as those in which dangerous pathogens and parasites, specifically PPNs, cannot establish or survive, are discovered but do not cause disease, or become established but only cause a minor illness that quickly goes away [30]. A soil is considered to have biological activity when one or more of the following conditions are met: (1) its suppressiveness is eliminated by biocides; (2) a small amount of suppressive soil can be transferred to conducive soil; (3) it is specific to a nematode species; (4) it can reduce root-knot and cyst nematode multiplication in the root zone; (5) it can be detected by baiting methods; (6) it is heat sensitive; and (7) it depends on soil density. The BCAs in nematode-suppressive soils can directly serve as nematode antagonists or they can indirectly prime plants and instigate their defense responses against PPNs to attain these characteristics. In a few soils with particular PPN suppressiveness, antibiosis and parasitism by BCAs have also been proposed. By using next-generation sequencing, Topalovi'c *et al*. [22] evaluated fungi and bacteria that had been isolated from dead or ill PPNs or characterized in soils that were suppressive of PPNs. They pointed out that as the microbiome can differ from one soil to another, soil suppression may work against the pertinent PPN species. The extent of this suppression may also be influenced by the soil's characteristics and the type of plant used. Plant genotype has an impact on the levels of BCA root colonization, as well as any potential metabolites and induced resistance. Poor host plants are less likely to harbors PPNs than nematode-susceptible plants, which means that more BCAs are required to suppress them. The induction of systemic resistance against RKNs was dependent on the plant species, despite the fact that two *P. chlamydosporia* strains were involved. Tomatoes were affected, but not cucumbers, and *M. incognita* infection and reproduction decreased [30]. Additionally, the *H. schachtii* tolerant sugar beetroot cultivar "Pauletta" allowed suppressiveness to be established in a separate monoculture of other sugar beetroot cultivars in *Heterodera schachti* infested soil without the initial yield reduction observed in susceptible cv. "Beretta" [31]. According to Botelho *et al*. [32], the biological and physicochemical characteristics of the coffee rhizosphere may determine how they affect the suppression of *Meloidogyne exigua* in actual field settings. As a result, these suppressive soils resulted in the highest coffee bean yields and roughly 83% *M. exigua* J2 mortality. Therefore, further research is needed to better understand the plant-nematode-microbe interactions in suppressive soils in order to offer new insights for the most effective use of suppressiveness.

Bionematicides from botanicals

Antagonistic cultivated plants

Antagonistic cultivated plants create anthelminthic substances as they develop, which act as antagonists to the nematodes through a variety of mechanisms [33]. The nematicide substances in the plant organs may be released into the soil, work internally to serve as nematode traps, or exhibit unfavorable reactions to PPNs. There are several antagonistic plant species, but *Tagetes spp., Azadirahta indica, Brassica spp., and Crotalaria spp.* are the most well-known types that are used to combat significant PPNs [34]. Various Tagetes (marigold) species may lower PPN populations through a variety of mechanisms, such as functioning as a subpar host or non-host, producing allelopathic substances, trapping the nematodes, or inducing nematode hostile flora and fauna. Marigold produces bithienyl and alpha-terthienyl derivatives that are poisonous to worms [35]. *T. patula, T. erecta*, and *T. minuta* are effective marigold species, notably against the nematode genus *Meloidogyne* and *Pratylenchus* [34]. *T. erecta, T. patula,* and *T. signata* reduced RKN galling in following susceptible tomato plants, in contrast to a tomato-to-tomato cycle. Neem (*Azadirahta indica*)-based treatments are most frequently employed in PPN control, despite the fact that the neem tree is typically thought to be hostile to many pests [36]. They might exhibit effective nematicidal behaviors. In addition, a variety of Brassica species, including mustard, rape, canola, and cabbage, can produce glucosinolates (GSLs). GSLs, a secondary metabolite, are hydrolyzed to produce poisonous and volatile isothiocynates (ITCs), which function as biofumigants against PPNs. The nematicidal qualities of ITCs released into the soil can therefore be attributed to aromatic GSLs (roots), indole GSLs (root and shoot), and aliphatic GSLs (seeds) when these repositories are alternated with PPN-susceptible plant species or grown as cover crops [37]. The biofumigation spectrum has been expanded to include antagonistic non-brassica species in order to suppress PPN. They can also combine to create volatile pathogen-repelling compounds. Sunn hemp (*Crotalaria juncea*) is frequently used as a cover crop and green manure because of its negative effects on RKNs in a variety of crops. In addition, *C. longirostrata* is added to the soil after being grown as a cover crop to lessen RKN galling. Instead of harmful exudates from the plant, its impact on PPN regulation may be caused by toxins released during microbial destruction [37]. For PPN regulation activities, several species were examined [38]. When bristle oats, oilseed radish, and maize (*Zea mays*) were interplanted or rotated, *Pratylenchus brachyurus* reproduction rates were reduced [39]. Intercropping velvet bean (*Mucuna pruriens*) or jack bean (*Canavalia ensiformis*) with maize resulted in an increase in growth of up to 34%, however *Pratylenchus zeae* population levels were reduced by 32%. Field conditions improved (22-190%) the yields of maize intercropped with jack beans [38].

Plant-related materials and substances

Another and more popular method for PPN control is to use the appropriate compounds by extracting them from the plants or adding plant parts to the soil. These materials are primarily made from or taken from hostile plants. Natural chemicals, organic acids, essential oils (EOs), and plant extracts and compounds are a few categories under which they might be categorized. However, not all of these classifications are solely associated with plants. For instance, the bacterium *Lactobacillus brevis* strain WiKim0069 and secondary plant metabolites [40-41] both create acetic acid. This acid can kill RKN J2 by degrading the nuclei, vacuolizing the cytoplasm, and damaging the cuticle [41]. Many organic acids, including butyric, propionic, amino, and formic acids, can be hazardous to PPN species [42]. They are created through the microbial breakdown of other substances in the soil, primarily those that are related to plant materials or residues, though they can also be the product of metabolites produced by soil organisms. Others have shown efficient against significant PPN species, including hydroxamic acids from the grass *Secale cereale* and sesquiterpene heptalic acid generated by the fungus *Trichoderma viride* [19], [43]. Additionally, EOs have undergone testing for PPN control. Four species of medicinal plants belonging to the Lamiaceae family underwent PPN control testing by Abd-Elgawad and Omer [44]. Natural constituents of neem, such as azadirachtin, kaempferol, thionemone, nimbidin, quercetin, and salannin, also have nematicidal effects. These substances can be absorbed by interplanted or treated plant roots when applied to soil. The pesticide business has also been interested in developing extraction methods for a number of natural nematicidal chemicals. Therefore, additional neem treatments that are effective include root dipping in neem leaf extracts, amending the soil with neem leaf extracts, mulching the soil with dried or fresh leaves, coating seeds with neem extract or oil, applying root exudates, or treating the soil with seed or kernel powder

[45]. The advantages of botanical extracts over synthetic nematicides are obvious.

Nematicidal products

While certain botanical-based nematicides are currently on the market, others are still in the works. Neemrich, Neemix, Neemazal, Neemgold, and Neemax are just a few of the potent neem-based nematicidal medicines that have been commercialized. Nemastop, on the other hand, is a commercial item that contains garlic (*Allium sativum*) extract (600 g crushed garlic cloves/1 water). Although it has been advertised as a PPN control method, this is not as effective on eggplant as commercially available biocontrol agents or even synthesized chemical nematicides [46]. Allicin (diallyl thiosulfinate), the powerful nematicidal component of garlic, continues to effectively suppress PPN in spite of this. The use of allicin may reduce *M. incognita* and increase tomato output [47]. Bionematicidal product labels from the manufacturer are frequently used to describe the host range of the product. They have not always been proven through fair trials [48]. When conditions are favorable, PPN control typically rises, leading to an increase in crop production as a result of a higher product concentration and/or longer exposure duration. For bionematicides to be effective generally, three key components are needed: (1) environmental and human health safety; (2) dependability of nematicidal impact; and (3) favorable economics. ITCs are used as active components in synthetic chemical nematicides, for instance. Although natural ITCs are useful as biofumigants against PPNs, they may have a similar biochemical mechanism of action against the targeted PPNs. The sensitivity and instability of soil food webs as well as the suppression of beneficial species have therefore been brought about by ITCs' detrimental effects, such as those of mustard biofumigants [49-50]. Because both synthetic and natural components of ITCs interact with amino acids and proteins in a non-specific and irreversible manner, Ntalli and Caboni [36] hypothesized that non-target organisms are also negatively impacted. Therefore, more research on their secure integration as components of pest management programmes is needed. Contrarily, pesticides that are related to ecological concerns and environmental risk include azadirachtin compounds, which are relatively safe. They disintegrate quickly and have quite limited potential soil movement. Azadirachtin is not poisonous to humans in its pure form, nor is it mutagenic. It additionally has relative selectivity. As a result, it is suitable for use in IPM programmes and safe for beneficial insects [34]. To determine the destiny or times of degradation of the chemicals from Tagetes spp. in soil, more research needs to be done. Researchers and other interested parties should keep in mind that safety is a relative concept that should be defined because these substances are still chemicals even though they are not manmade. To provide greater safety for human application than the well-known synthetic chemical nematicides, a number of plant materials/extracts have been synthesized. Although Sikora *et al*. [38] claimed that antagonistic plants are highly alluring instruments for PPN management, there may be further ones that might be discovered. Additionally, methods for effective and versatile applications should be sought after. Other benefits of hostile plants include their successful improvement of the soil's properties. To improve soil quality, they serve as organic matter and greenery [51]. Additional benefits can apply to particular groupings of hostile plants. As an attractive example, consider increasing the action of biocontrol agents against PPN in addition to their direct impact on lowering insect damage. In contrast to the bacteria found on soybean roots, rhizobacteria isolated from the roots of rival plant species *Ricinus communis, Mucuna deeringiana,* and *Canavalia ensiformis* were able to significantly reduce the populations of *Meloidogyne incognita* and *Heterodera glycines* on soybean plant roots. Due to their numerous methods and broad spectrum, Grubii'c *et al*. [34] hypothesized that these plants may still have a selective activity against each pest class. Additionally, these legume-related antagonists have the ability to fix atmospheric nitrogen, which increases soil fertility. It should be investigated whether using any of the botanicals to control PPN is economically feasible. Even a technique with strong nematicidal characteristics to the desired PPNs will fail if economic conditions are unfavorable. Economic success depends on the grower's desire to prevent crop losses brought on by nematode pests, the relative costs of utilizing this bionematicide compared to alternative PPN control options, the commodity's value (e.g., per acre), and its price in the relevant market. As a result, a grower should be informed of the indirect advantages of these safe nematicides, such as how they can be used to prevent ecological contamination, health risks, and nematode resistance to chemical nematicides. Such a development in agriculture would promote their use by farmers. Other regulations could increase profitability and cut costs for a certain herb. Due to the great value of marigold as an ornamental plant, for instance, marigold seeds are more expensive than seeds of cover crops. Therefore, it was indicated by Grubiši´*et al*. [34] that if the seeds were widely commercialized as cover crops for PPN management programmes, their costs would be reasonable or even reduced.

Modern techniques

In order to safely and effectively control PPN, our targeted agroecosystems must overcome serious hurdles that call for cutting-edge techniques and creative thinking. The increased prohibition of many powerful but synthetic chemical nematicides, increased vertical and horizontal agricultural expansion to increase and improve food production, the frequent emergence of resistance-breaking nematode pathotypes, global warming supporting rapid PPN reproduction and spread, and the discovery of new PPN species [52] (to name but a few related to aggravated nematode damage) are some of the biggest challenges. In order to best meet these anticipated ecological windows of the pests and pathogens, new PPN management approaches and strategies should look for more durable BCAs and related materials [53]. For instance, effective techniques for better comprehending biological and ecological aspects of BCAs should be used [54]. Additionally, specific wavelengths through near-infrared spectroscopy could be utilized to find collections of soil nematodes with various roles linked to particular groups of soil organic matter [55]. The development of bioactive substances with naturally occurring multifunctional derivatives, such as nematicidal activity, is also ongoing. The chitin oligosaccharide dithicyclobutane (COSDTB) derivative is an example of such a derivative at 2 mg/mL, the 1, 3-dithicyclobutane-N-chitosan oligosaccharide could reduce the hatching rate of M. incognita eggs by up to 90% and kill *M. incognita* J2 at 4 mg/mL by 94% [56]. A recent review [57] examined the function of silicon in promoting plant resistance to a range of damaging bacterial and fungal invasions. Since silicates' salts can also reduce Meloidogyne paranaensis populations on coffee seedlings [58], they ought to be used more often in IPM programmes in specific locations with different pathogen species. Optimizing the benefit of connected industries will also result from developing industrial wastes as value-added goods for PPN control. Waste materials including orange bagasse, soybean hulls, rice husks, chicken litter, and common bean hulls were evaluated for *M. javanica* control in the glasshouse [59]. Their mixtures, which comprised orange bagasse, soybean hulls, and powdered bean hulls, ranged from 55 to 100% RKN control. Other powerful BCAs or their metabolites against PPNs, such as *Mortierella globalpina* and *Rhodoblastus acidophilus* strain PSB- 01, are presently being studied. However, it has been discovered that nanoparticles [60] have advantageous physical and chemical characteristics against nematodes. With a few possible weaknesses, they have demonstrated strong Plant-parasitic nematodes (PPN) control.

There are several application methods that have not undergone extensive testing to create them, such as spraying BCAs around the base of plants, using a slow-release system in real life, or dipping root plugs in BCA solutions. Crop protection and pest control must move forward with systematic experiments and field trials evaluating the aforementioned strategies in diverse situations to demonstrate their value with workable, affordable insights.

CONCLUSION

Given the significant and detrimental effects of nematicides, a synthetic chemical, there is a wealth of literature on employing safe management techniques for PPNs. Different materials, including BCAs, botanicals, poor- or non-host crops, and other cutting-edge techniques, may be used in these approaches, along with a variety of tactics and strategies. However, as many BCAs, for instance, are less predictable, less efficient, and/or slower acting in nematode control than synthetic chemicals, it is primarily necessary to create and/or optimize such safe approaches. Therefore, it is important to acknowledge and seriously implement agricultural practices that support the conservation biocontrol of PPNs. Additionally, bionematicides can be utilized in IPM plans in a variety of ways that make them superior to or complementary to these chemicals. They can also have additive or synergistic effects with other agricultural inputs. Finding the best performance from the many bionematicides that are currently available or are anticipated to become widely accessible soon. In order to increase soil fertility within sustainable agricultural production systems, research priorities for utilizing such pertinent and cutting-edge techniques should be established. Understanding the intricate web of interactions between biotic and abiotic variables that are in direct contact with these bionematicides will be necessary to maximize their benefits. Therefore, it is important to focus research on the biology and ecology of these bionematicides; this research may even require the application of advanced, previously proven approaches. While this is going on, stakeholders like nematologists and agronomists can instruct, aid, and direct extension agents and farmers to improve the quality of their harvest. This can be done by improving the application efficacy of these bionematicides so as to lessen the negative impact that pests have on their crops.

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