TAS
Trends in
Agricultural Sciences

OPEN ACCESS

Overview of the Use of Plants and Plant Based Materials for the Management of Plant Parasitic Nematodes

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ABSTRACT

The quest to increase food production has resulted in the development of many programmes that can support food production in several developing countries; however, crop yields are still at a low ebb. This is attributable to marginal soils and various attacks by pests and diseases. Many plant parasitic nematodes are soil-borne pathogens; they are ubiquitous and can attack a number of cultivated crops causing yield losses globally. Control measures have been with the use of synthetic nematicides but they come with their drawbacks. Authors have suggested the use of plants and plant-based materials as plant parasitic nematode management strategies because of the promising results obtained. Unlike synthetic nematicides, natural nematicides from plants and plant-based materials are easy to come by and are environmentally friendly. On the other hand, some authors have reported that their effects on plant parasitic nematodes are temporary. However, methods of application of these materials amongst other factors can greatly affect their effectiveness on plant parasitic nematodes. The objectives of the review were to reveal some important plants and plant based materials that have been successfully used for nematode management, various types of natural nematicides contained in some plants, methods of applying them to the soil and the mechanisms by which they control nematodes.

KEYWORDS

Natural nematicides, essential oils, plant extracts, cover crops, incorporation, pyrrolizidine

INTRODUCTION

The increasing demand for food following increasing populations in many developing countries has resulted in an increase in the development of many agricultural policies and programs by successive governmental and non-governmental organizations to support crop production. However, despite these efforts, actual yields are still considerably lower than potential yields in many crop fields. This is partly due to infertile soils and attacks by pests and diseases[1]. Plant parasitic nematodes are major limiting biotic factors affecting crop production in many rural communities. Farmers do not notice their attacks, since the symptoms expressed on plants by nematodes are similar to those caused by abiotic stresses[2,3].

ISSN: 2957-9449 (Online)
ISSN: 2957-9430 (Print)
https://doi.org/10.17311/tas.2024.231.254

Received: 11 Mar. 2024
Accepted: 18 Jul. 2024
Published: 30 Sep. 2024

Plant parasitic nematodes attack virtually all cultivated crops, causing significant reductions in yields and qualities of harvested crops[4]. The activities of these nematodes are even more severe in areas characterized by sandy soils and high temperatures[5]. A vast number of them are soil-borne pathogens; and as such they attack plants mainly from the root causing a number of distortions, including gallings, lesions and abbreviation of root systems on root systems[4]. The aftermath effect of these is reductions in the efficiency by which the plant root system performs its normal functions including absorption and translocations of water and minerals respectively from the soil to the parts of the plants where they are needed and this in turn results in yield reductions. Sometimes these nematodes interact with other pathogens, to form complex diseases, hence increasing disease severity and yield losses in crop fields[6].

Based on these facts, it becomes necessary to manage the populations of nematodes to avoid yield losses in crop fields. Chemical nematicides such as carbofuran have been used for the control of plant parasitic nematodes over the years and records have it that, it has been effective in controlling nematodes[7]. However, they are expensive and pose hazards to man and non-target organisms, hence their usage is being phased out in many developing countries. These have resulted in the development of other nematode management strategies that can effectively control plant parasitic nematodes and replace the use of synthetic nematicides[7]. The use of plants and plant-based materials as soil organic amendments is on the increase due to results obtained by earlier workers[3,4,8-10]. Plants and plant based materials include actively growing plants, plant based composts, plant based kitchen wastes and plant based agricultural/industrial by-products. To a large extent, their uses as soil organic amendments have recorded successes[4]. However, some authors have shown that their effects on plant parasitic nematodes are inconsistent. However, their effectiveness largely depends on the rate of application, type of plant-based materials used and method by which they are applied to the soil[11].

Unlike the use of synthetic nematicides, the use of plants and plant-based materials for nematode management strategy represents an ecologically friendly strategy for nematode control. This is due to the fact that they are biodegradable, readily available and pose little or no hazards to users, non-target organisms and the environments[12]. In addition, their effects have been shown to have dual effects, in that, they suppress the populations of plant parasitic nematodes and correspondingly increase the yields of plant parasitic nematode infected crops[8,13].

However, despite many successful reports by authors on the use of plants based materials as strategies for plant parasitic nematode management, little is known on mechanisms by which these organic materials kill nematodes, effective methods and rates of applications and natural pesticides contained in them. The objectives of the review were to reveal some important plants and plant based materials that have been successfully used for the management of plant parasitic nematodes, types of natural pesticides contained in them, methods of applying them to the soil and the mechanisms by which they control nematodes.

PLANTS AND PLANT-BASED MATERIALS FOR NEMATODE MANAGEMENT STRATEGIES

The use of plants and plant-based materials for nematode management strategies involves the use of plants or plant-based materials for the management of plant parasitic nematodes. This could be achieved mainly by working plant-based materials (leaves, stems, roots or whole plants), plant-based kitchen wastes (yam peels, cassava peels, orange peels, etc.), plant-based composts, agricultural/industrial by-products (oil palm effluents, soybean cake, etc.) into the soil either in dried or wet form[14]. In some cases, plants are cultivated as cover crops and allowed to grow in the field at a given period to incorporate them into the soil[4,8], while in some cases food crops are cultivated in alleys of trees such as *Leucaena leucocephala* that can release nematode toxic substances while actively growing[15,16]. It is important to note that the effectiveness of the use of plants or plant-based materials for nematode control highly depends on the type of plants and plant-based materials used. Plants embedded with

Table 1: Plants and plant-based materials effective against some plant parasitic nematodes

Plant/plant residues	Plant parasitic nematodes	Method of application	References
Sunn hemp	*Meloidogyne incognita*, *Rotylenchulus reniformis*, *Xiphinema* spp., *Pratylenchus brachyurus*, *Heterodera glycines* and *Helicotylenchus*	Soil amendment, cover crop, plant extract and leachates	Amulu *et al.*[4], Ogundele *et al.*[8], Amulu *et al.*[9], Adekunle[12], Entsar[19], Germani and Plenchette[20], Frederick *et al.*[21], Chellemi *et al.*[22], Waisen *et al.*[23], Mosjidis and Wehtje[24], Marla *et al.*[25], Chen *et al.*[26] and Hooks *et al.*[27]
Mexican sunflower	*Meloidogyne incognita*, *Xiphinema*, *Pratylenchus brachyurus*, *Helicotylenchus multicinctus*, *Rotylenchulus reniformis*, *Paratrichodorus minor* and *Tylenchulus semipenetrans*	Plant extract, soil amendment, cover crop, compost, soil amendment and rotation crop	Amulu *et al.*[4], Amulu *et al.*[9], Amulu *et al.*[10], Adekunle[12], Coelho *et al.*[13], Odeyemi and Adewale[28], Nunes *et al.*[29], Akpheokhai *et al.*[30], Osei *et al.*[31] and Kimenju *et al.*[32] and Amulu *et al.*[33]
Sudangrass	*Meloidogyne incognita*, *Helicotylenchus dihystera*, *Rotylenchulus reniformis*, *Heterodera glycines* *Pratylenchus penetrans*, *Pratylenchus*, *Longidorus*, *Xiphinema* and *Paratrichodorus*	Soil amendment	LaMondia *et al.*[34] and Djian-Caporalino[37]
Gliricidia sepium	*Meloidogyne incognita*, *Pratylenchus* spp., *Paratylenchus* spp. and *Hoplolaimus* spp.	Plant extract and alley crop	Adekunle[15], Farzanaa and Hussain[38] Tavella *et al.*[39] and Adekunle and Akinlua[40]
Lemon grass	*Meloidogyne incognita*, *Meloidogyne graminicola* and *Meloidogyne javanica*	Plant essential oil	Chavan *et al.*[41] Oyedunmade and Izuogu[42] and Sinha *et al.*[43]
Leucaena leucocephala	*Meloidogyne incognita*, *Pratylenchus* spp., *Paratylenchus* spp. and *Hoplolaimus* spp.	Alley crop and soil amendment	Adekunle and Aderogb[7], Adekunle[15] and Kimenju *et al.*[32]
Velvet bean,	*Meloidogyne incognita*, *Pratylenchus*, *Helicotylenchus* spp., *Scutellonema* spp., *Tylenchorhynchus* spp. and *Rotylenchus* spp.	Cover crop	Adediran *et al.*[44]
Marigold	*Meloidogyne incognita*, *Meloidogyne javanica*, *Rotylenchulus* spp.	Cover crop, soil amendment and trap crop	Das *et al.*[3], Ogundele *et al.*[8], Adekunle[12], Hooks *et al.*[27], Priyanka *et al.*[45] and Evenhuis *et al.*[46]
Siam weed	*Meloidogyne incognita*, *Pratylenchus* spp., *Helicotylenchus* spp., *Scutellonema* spp., *Tylenchorhynchus* spp. and *Rotylenchus* spp.	Cover crop, soil amendment, plant extracts, compost and cover crop	Abolusoro *et al.*[17], Adediran *et al.*[44] and Oladele and Adekunle[47]
Brassica spp.	*Meloidogyne javanica* and *Rotylenchulus* spp.	Plant extract	Das *et al.*[3] and Wang *et al.*[48]
Hibiscus	*Meloidogyne incognita*	Intercrop	Adepoju *et al.*[49]
Neem	*Meloidogyne incognita*	Plant extracts and soil amendment	Alzohairy[50] and d'Errico *et al.*[51]
Ocimum spp.	*Meloidogyne incognita* and *Meloidogyne graminicola*	Essential oil	Chavan *et al.*[41], Sinha *et al.*[43], Ntalli *et al.*[52] and Rech *et al.*[53]

natural nematicides top the list of plants or plant-based materials that have been used successfully for nematode management strategies[4,11,17,18]. A summary of plants and plant-based materials that have been confirmed to be effective in their actions on a number of plant parasitic nematodes are listed in Table 1.

PLANTS AND PLANT BASED MATERIALS AND NATURAL NEMATICIDES THEY CONTAIN

Sunn hemp, *Crotalaria juncea*: The Sunn hemp, *Crotalaria* spp. is a tropical plant that is found growing wild in many forests in African Countries. It is a leguminous plant, hence rich in protein and as such can be used as fodder crops for feeding livestock. The plant is effective in controlling a number of plant parasitic nematodes[12]. It is known to produce nematicidal allelopathic compounds including monocrotaline and pyrrolizidine alkaloids which have been confirmed to be lethal to several plant parasitic nematodes[54]. These substances, alongside other substances, are released by the plant while actively growing and following decomposition[4,12,54] kill plant parasitic nematodes when their concentrations are high. The application of 1,2-dehydropyrrolizidine alkaloids isolated from *Crotalaria* plant on plant-parasitic nematodes revealed that the pyrrolizidine alkaloids exhibited toxic effects on different plant parasitic nematodes[55]. Monocrotaline is the predominant pyrrolizidine alkaloids embedded in *Crotalaria* spp.[54,56,57].

Like other leguminous plants, they can fix nitrogen directly into the soil[4]. This may also contribute to their effectiveness in reducing the populations of plant parasitic nematodes. This is because nitrogen is mineralized in soils to form ammonia or ammonium compound and these compounds have been reported to kill plant parasitic nematodes[4,58].

Marigold, *Tagetes* spp.: The *Tagetes* (marigold) belongs to the Asteraceae family and is native to America and its cultivation has extended to other regions of the world. Several species of the plant including *Tagetes erecta*, *Tagetes patula*, *Tagetes minuta* and *Tagetes tenuifolia* are known to contain phytochemical substances that are antimicrobial[45]. Recently compounds such as thiophenes: 5-(3-buten-1-ynyl)-2,2-bithienyl, 5-(4-hydroxy-1-butynyl)-2, 2-bithienyl and 5-(4-acetoxy-1-butynyl)-2, 2-bithienyl, acetylenes, phenylpropanoids, alkaloids, flavonoids, carotenoids, terpenoids, citric and malic acids have all been isolated from marigold plants[27,59-62] and some of these compounds have been reported to be nematicidal[63-65].

The polythienyls group has been the most studied among them on plant parasitic nematodes[60]. These sulphur containing compounds (e.g., α-terthienyl and bithienyl) have been reported to possess nematicidal properties[27]. Laboraz tory and field experiments have indicated that they are lethal to several plant parasitic nematodes[12,66,67]. Hamaguchi *et al.*[66] investigated the nematicidal activities of the marigold, exudate α-terthienyl on *Caenorhabditis elegans* and *M. incognita* and their findings revealed that α-terthienyl was effective in suppressing the populations of the nematodes.

Field studies using marigold as soil organic amendments have produced similar results in their actions on root-knot nematodes, lesion nematodes, reniform nematodes, *Heterodera* spp., *Helicotylenchus* and *Dolichodorus* following incorporation or when used as intercrops[8,56]. The findings of Adekunle[12] demonstrated that the seedlings of African marigold chopped and worked into the soil 2 weeks after transplanting, suppressed the populations of *Meloidogyne incognita* infecting cowpea and soybean cultivars. Evenhuis *et al.*[46] reported that *Tagetes erecta* plant parts left on the fields following harvesting continued to suppress the populations of *Pratylenchus penetrans*. When *Tagetes patula* cv. Creole and *Tagetes erecta* cv. Crackerjack were used as rotation crops with rye crops and also compared with synthetic nematicide applied to the field before transplanting tobacco. The results indicated that the two marigold plants suppressed the populations of *P. penetrans* and increased the yields of the crop[66]. They mentioned that the marigold plants were at par with the synthetic nematicide in their actions on the nematode.

Siam-weed *Chromolaena odorata*: The Siam-weed, *Chromolaena odorata* is a fast-growing and invasive weed growing in crop fields and road sides in African and Asian countries. It is usually a difficult and problematic weed in crop fields and contains a number of phytotoxic substances. Recent study, data presented by Eze and Jayoye[67] revealed the presence of a number of glycosidic compounds (phenolics and terpenoids). Alkaloids, xanthones and fatty acids were also listed in their data. Similarly, several phenolic compounds including; 1,2-dehydropyrrolizidine alkaloids, flavonoids, tannins and saponnins were identified in the plant; some of these compounds were tested on *M. incognita* and reported the high toxicity of 1,2-dehydropyrrolizidine alkaloids on the nematode[68,69]. Direct application as plant extracts and as soil organic amendments have also been shown to suppress the populations of plant parasitic nematodes[17,47].

The application of botanicals including siam weed leaves and roots each at 30 and 50 kg/ha and furadan at 1.5 and 2.5 kg a.i/ha on cowpea field infested with plant parasitic nematodes significantly reduced the populations of *Pratylenchus* spp., *Helicotylenchus* spp., *Xiphinema* spp. and *M. incognita* increased the yields of cowpea[17]. Similarly, Oladele and Adekunle[47] reported significant reductions in the populations of *M. incognita*, *Pratylenchus* and *Tylenchus* following the application of siam weed and Mexican sunflower at 7 and 14 seedlings per plot on field planted to okra cultivars NH47-4 and LD88.

***Brassica* spp.:** The *Brassica* belong to the family Brassicaceae and consists of about 350 genera and about 3500 species[70]. Brassica is the most important of all the genera of this family[70,71]. The phytochemical compounds of *Brassica* spp. have been identified by Cartea *et al.*[70] and Dahlin and Hallmann[71]. Cartea *et al.*[70] listed a number of phytochemical compounds including phenolics, polyphenols, phenolic acids, flavonoids, carotenoids (zeaxanthin, lutein, β-carotene), alkaloids, phytosterols chlorophyll, Isothiocyanates, glucosinolates, terpenoids and glycosides.

Some of these compounds have been demonstrated to be toxic to plant parasitic nematodes. Studies have revealed that *Allyl Isothiocyanate* extracted from *Brassica* plants was toxic to several plant parasitic nematodes[72]. Almost all members of the Brassicaceae family produce glucosinolates, which hydrolyze in the soil to form isothiocyanates[62,73]. In soil, the isothiocyanates often have nematicidal effects on several plant parasitic nematodes[73]. The nematicidal activity of *Brassica* is attributable to the effect of the isothiocyanates concentration released by the plants following incorporation and decomposition[60,72,73]. Studies carried out on the effects of parts of *Brassica* spp. including rapeseed leaf or seed extracts or specific glucosinolates were demonstrated to be toxic to *Caenorhabditis elegans*, *Xiphinema americanum*, *Heterodera schachtii* or *Globodera rostochiensis* only when the glucosinolates were enzymatically broken down to isothiocyanates[60]. Similarly, Adekunle and Aderogba[7] investigated the effects of *Brassica hirta* and *Broccoli juncea* soil amendments on *Meloidogyne javanica* and *Tylenchulus semipenetrans*, plant parts, rich in glucosinolate-precursors of the isothiocyanates that are highly lethal to plant parasitic nematodes were applied to soil, based on the isothiocyanates lethal concentration (LC) values. This provided reliable rates for plant parasitic nematode suppression. Glucosinolates at lethal concentrations of LC_{50} and LC_{90} of the two soil amendments significantly reduced the populations of the nematodes. However, at all the biomass levels of the soil ammendments used, *Banksia hirta* suppressed the population of the nematode more than *Brassica juncea*. They suggested that glucosinolate content of *B. juncea* was probably not enough to reduce the populations of the nematode at the same biomass levels as *B. hirta*. The toxicity of allyl isothiocyanates against a number of plant parasitic nematodes is well documented[60,73,74].

Mexican sunflower, *Tithonia diversifolia*: The Mexican sunflower, *Tithonia diversifolia* (Hemsely) A. Gray (Asteraceae), is a common weed that originated from Central America but has since been distributed to other regions of the world[75,76]. It is usually found growing aggressively on roadsides, crop fields and abandoned lands and buildings in Nigeria[75-77].

Mexican sunflower is known to contain allelochemical compounds such as flavonoid ($C_{15}H_{12}O_3$), sesquiterpenes lactones ($C_{10}H_{18}O_5$), hispudin ($C_{12}H_{18}O_{11}$), tagitinin A ($C_{11}H_{16}O_{15}$), tagitinin C ($C_{11}H_{16}O_5$), monoterpenes and terpenes[78,79]. These compounds are known to exhibit antimicrobial activities, however, little is known about their effects as a natural nematicide in nematode management strategies. Most studies on Mexican sunflowers reported the plant as a bio-fertilizer and as a bio-insecticide[28,77,79-81,].

However, recent studies have shown that they can be effective in controlling several plant parasitic nematodes[4,29,30,82]. Akpheokhai *et al.*[30] conducted a laboratory and a pot experiments to determine the nematicidal effects of *T. diversifolia* amongst other botanicals on *M. incognita*. In an *in vivo* experiment, eggs and juveniles of the nematode were exposed to 0, 25,000 and 50,000 mg/kg concentrations of water extracts of the plant parts. In the *in vitro* experiment, air-dried milled samples of the plant parts at 50 and 100 kg/ha were applied to soybean cv. The TGX 1440-1E inoculated with eggs of *M. incognita*. The result showed that water extracts of all four botanicals including *T. diversifolia* at 25,000 and 50,000 mg/kg inhibited egg hatch by over 70% within ten days. The juvenile mortality at 50,000 mg/kg concentration was 89% for *T. diversifolia*. The milled plant parts significantly reduced root gallings and suppressed the populations of the nematode. Similarly, Abdel-Rehman *et al.*[83] conducted an *in vitro* study to evaluate the effects of different botanicals including Mexican sunflower on root-knot infecting tomatoes. The results indicated that extracts of all the plants including Mexican sunflower inhibited egg hatching of nematode and resulted in 100% mortality of the second stage juveniles of *M. incognita*.

Although, works on the toxicity of the phytochemicals isolated from the plant on nematode is scanty in literature, sesquiterpenes lactones, terpenes and monoterpenes which are among the compounds embedded in the plant have been reported to be lethal in plant parasitic nematodes[61]. Studies involving sesquiterpenoids have demonstrated nematode toxicity at 1100 µg/mL *in vitro* against *M. incognita*. Works on the nematode toxicity of terpenes and monoterpenes have been well documented[84,85].

Sudangrass, *Sorghum sudanense*: The sudangrass (Sorghum sudanense) belongs to the family Poaceae, it has high palatability and as such are used in feeding livestock. The plant and its relatives are can withstand harsh climatic conditions including drought and heat. They are used as cover crops to add nitrogen to soil, suppress weed growth and plant parasitic nematode populations. Curto *et al.*[86] have shown that the plant is known to release bioactive compound known as dhurrin. This compound breaks down to form hydrogen cyanide which is highly toxic to plant parasitic nematodes[86,87]. Another bioactive compound that has been identified in the plant is sorgoleone[88], though little information is known on its effects on plant parasitic nematodes. The plant has been used effectively to suppress the populations of several plant parasitic nematodes including *Helicotylenchus dihystera*, *Rotylenchulus reniformis*, *M. incognita*, *Heterodera glycine* and *Pratylenchus penetrans*[34-36]. Field trials revealed that the incorporation of *Sorghum sudanense* sudangrass cv. 'Piper' and sudangrass hybrid (*S. bicolor*×*S. sudanense*) '270911' on-field infested with *Meloidogyne* spp. grown to vegetable crops significantly suppressed the population of the nematode. Further studies revealed that the two sudangrasses were poor hosts to the nematode[37].

Velvet beans, *Mucuna pruriens*: The velvet bean (*Mucuna pruriens* L.) DC. var. utilis (Wall. ex Wight) Baker ex Burck). It is a tropical legume that is native to Africa but can grow in some tropical regions in Asia. It is an annual, though sometimes short-lived perennial climbing plant. The plant is found growing vigorously in crop fields, farms and tropical forests in African countries. The plant can be used for a variety of purposes including food, animal feed, medicine, green manure, cover crops for weed and plant parasitic nematode suppression[89]. Several phytotoxic substances have been identified in the plant and these include L-dopa (L-3, 4-dihydroxyphenylalanine), tryptamine, serotonin, N,N-dimethyltryptamine, 5-methoxydimethyltryptamine, bufotenine and 5-methoxydimethyltryptamine[90,91]. These compounds have been reported to kill *M. incognita*[92]; Zasada *et al.*[90] reported the suppression of *M. incognita* following application of aqueous extract of velvet beans in soil infested with the nematode.

Neem, *Azadirachta indica*: The neem tree, *Azadirachta indica* is native to India and has been indigenized in many parts of the world. The importance of the crop to man cannot be over emphasized in that its usage cuts across tribes and countries. It has been found useful in both modern and traditional medicines, production of bio-fertilizer, bio-pesticides, bioremediation and aesthetic purposes[93].

The plant contains a number of biologically active natural chemicals including azadirachtin, meliacin, gedunin, nimbidin, nimbolides, salanin, nimbin, valassin and meliacin. The seed contains tignic acid which gives the oil its denotative smell. Neem kernels contain 30-50% oil and hence are used in making soaps, pesticides and pharmaceutical products[94].

Additionally, other bioactive compounds such as amino acids, polysaccharides, flavonoids, coumarins, dihydrochalcones, tannins and aliphatic and sulphureous have been identified in the plant[95,96]. The four best limonoids compounds are: Azadirachtin, salannin, meliantriol and nimbin and these have been reported to kill a number of insects and pathogens[94].

A number of authors have revealed that some of these bioactive compounds, especially azadirachtin are highly toxic to plant parasitic nematodes[69,94]. Several studies have demonstrated the toxicity of neem oils, oil cakes, extracts, leaves, roots or root exudates against many species of plant parasitic nematodes[75,94,97]. In some cases, they are usually used as soil organic amendments or bio-fumigation by working the leaves and oil cakes into the soil for nematode control[98]. They can also be applied as plant extracts on plant parasitic nematodes[69,96,97,99]. Its refined product azadirachtin is one of most commercialized botanical nematicides[18].

***Leucaena leucocephala*:** The *Leucaena leucocephala* (Lam.) de wit., belongs to the family Leguminosae, a fast-growing tree and that originated from America but has since been distributed to other part of the world. The plant is referred to as miracle tree because of its multiple uses. It is an important source of biofertilizers and can be used in alley cropping systems, land management and reclamation, landscaping[15,100].

The phytochemistry of the plant has been identified by earlier workers[7]. They listed 10 chemicals contained in the plants. These chemicals include; mimosine, quercetin, gallic, protocatechuic, p-hydroxybenzoic, p-hydroxyphenilacetic, vanillic, cafeic and p-coumaric acid. Some of these have been reported to exhibit nematicidal effects on nematodes. Take for instance, quercetin, isolated from extracts of leaves of *L. leucocephala* was tested on eggs and juveniles of *M. incognita* at 0.8, 0.4 and 0.2% *in vitro* and the results indicated that all the rates of the substance were toxic to eggs and juveniles of the nematode[7]. It has been used to control several plant parasitic nematodes in alley cropping system[15]. Adekunle[15] investigated the pathogenicity *Meloidogyne incognita*, *Pratylenchus* spp., *Paratylenchus* spp. and *Hoplolaimus* spp. on three cultivars of okra grown in alleys between three years old *L. leucocephala* tree and the results showed that the okra cultivars in alley fields had lower root gallings by the root-knot nematode, lower populations of the plant parasitic nematodes and higher pod weight of okra compared to those in non-alley fields. Many other authors have reported the suppressions of plant parasitic nematodes following incorporation and consequently decomposition of the plant residues[40]. In addition, the plant fixes nitrogen to the soil, like every other legume. The nitrogen dissolves in soil moisture, mineralizes and consequently saturates the soil with ammonia. This nitrogenous compound (ammonia) has been reported to be toxic to plant parasitic nematodes as stated earlier[58,97].

***Gliricidia sepium*:** The *Gliricidia sepium* (Jacq.) Kunth ex Steud. is a semi-deciduous shrub, that grows well in the tropical areas. The shrub is native to Central America and Northern America and has since been distributed to many tropical and sub-tropical regions of the world[101]. It is a leguminous tree and is used for many purposes such as fuel (firewood), fodder, mulch, landscaping and green manure[39,101]. The plant has been reported to control several insect pests and pathogens, including plant-parasitic nematodes[40,101]. This fact has been supported by the identification of many bioactive compounds in some parts of the plant[40]. Phyto-chemical analysis showed that the plant leaves contained phenolic compound and a carboxylic acid, while the roots showed the presence of aromatic amide, phenolic compound and carboxylic acid[40]. Some of these compounds are known to be highly toxic to plant parasitic nematodes. Adekunle and Akinlua[40] reported that the direct applications of extracts of leaves and roots of *Gliricidia sepium* at 80,000 and 40,000 mg/kg on *M. incognita* on okra resulted in reduced nematode populations, reduced gallings and increased fruit yields of the vegetable crop.

***Ocimum* spp.:** The *Ocimum* spp. are aromatic plants belonging to the family Lamiaceae, originated from Indian and have been introducing to other regions of the world[102]. A large number of essential oils extracted from different Lamiaceae have been shown to exhibit nematode toxicity on several plant parasitic nematodes[103]. The essential oils extracted by some workers including mixtures of terpenes and terpenoids combined aliphatic and aromatic compounds[53]. Isomers of 1,2-epoxymenthyl acetate, L-carvone, piperitone, pulegone, (−)-carvone, trans-anethole, eugenol, borneol, geraniol, limonene, γ-terpinene, o-cymene, carvacrol, 1,8-cineole, α-pinene, camphor, terpinen-4-ol, eucalyptol, ã-terpinene, methyl eugenol, estragole, thymolm, oleanolic acid, rosmarinic acid, ursolic acid, linalool and β-caryophyllene are some of the most important essential oils isolated from Lamiaceae plants. Many of these oils have been tested and confirmed to be nematode toxic[104,105].

The essential oils extracted from *Mentha* spp. (−)-carvone and limonene, isomers of 1,2-epoxymenthyl acetate and piperitone), *Origanum* spp. (carvacrol, thymol) and *Coridothymus* spp. (carvacrol) were reported to be highly toxic to *Meloidogyne* spp. causing high mortality of the second-stage juveniles, inhibiting egg hatch and reducing gallings[106]. They emphasized that thymol, carvacrol and (−)-carvone were the most toxic to the nematode in *in vitro* and greenhouse experiments.

The essential oils of *O. vulgare*, *O. dictamnus*, *M. pulegium* and *Melissa officinalis* were reported to be highly toxic to *M. incognita*[53]. Nasiou and Giannakou[106] demonstrated that the application of carvacrol at 20 ppm on *M. javanica* inhibited exhibited high mortality of second stage juveniles and inhibited egg hatch of the nematode. Other components of the plants such as L-carvone, piperitone, pulegone, eugenol, geraniol, limonene, γ-terpinene, o-cymene, α-pinene, camphor, terpinen-4-ol, eucalyptol, ã-terpinene, thymolm, oleanolic acid and rosmarinic acid, have been reported to be toxic to nematode[107,108].

The applications of water extracts from plant species within the family without the use of toxic solvents has also been shown to be lethal against a number of plant parasitic nematodes. A study conducted to test the toxicity of five botanicals including *O. sanctum* on *M. incognita* in a laboratory experiment. Five concentrations of water soluble extracts from the five botanicals were prepared and added to petri dishes containing eggs of the nematode. The results showed that *O. sanctum* was the most toxic of all the botanicals on the nematode. There was no hatching of egg within 48 hrs in comparison with 34.8% hatching in control[109]. The applications of water extracts of *Mentha* spp., *O. vulgare* were found be toxic on *M. incognita* and *M. javanica*[110,111].

Agricultural/industrial wastes: These are organic waste materials or agro-industrial waste materials that are of plant origins such as soybean cakes, effluents from oil palm mills, kitchen wastes, corn hubs, expired food products, sawdust, charcoal, rice husk, yam peals, cassava peels and many more[14,112]. These materials have been found to have potential to manage the activities of plant parasitic nematodes[112,113]. They release nematode toxic compounds following incorporation and degradation in the soil. Their effectiveness in the suppression of nematode populations depends on the toxic compounds released by the waste materials

Table 2: Agricultural and industrial wastes toxic to plant parasitic nematodes

Agro/industrial waste	Plant parasitic nematodes	References
Rice husks	*Meloidogyne* spp.	Ali and Singh[114]
Kitchen waste		
Sawdust	*Meloidogyne incognita*	Prakash and Singh[113] and Siddiqui and Alam[115]
Oil palm sludge	*Meloidogyne incognita*	Oyedunmade[116]
Yard waste compost	*Criconemella* spp. and *Pratylenchus* spp.	Chindo *et al.*[112]
Locust bean husks	*Meloidogyne incognita*	Makhubu *et al.*[117]
Biochar (bitter leaf origin)	*Meloidogyne* spp.	Chindo *et al.*[112]
Biochar (cassava peels)	*Meloidogyne* spp.	Chindo *et al.*[112]
Fruit peels (citrus)	*Meloidogyne incognita*	Abolusoro *et al.*[118], Manneh *et al.*[119] and Talbot and Treseder[120]
Maize stover	*Meloidogyne incognita*, *Helicotylenchus* and *Xiphinema*	Chindo *et al.*[112]
Cassava peels	*Meloidogyne incognita*	Chindo *et al.*[112], Manneh *et al.*[119] and Talbot and Treseder[120]
Biochar	*Hirschmanniella*	Oladele and Adekunle[47]

used; hence their effectiveness largely depends on the type of agricultural waste material used. Agricultural and agro industrial waste materials that have been successfully used in the management of plant parasitic nematodes are listed in Table 2.

Use of plant and plant-based materials for nematode control: Generally, there have been conflicting results on the use of soil organic amendments including those of plant origins in nematode control[11]. Some authors have shown that the use of plant materials for plant parasitic nematode management strategy temporarily or failed to suppress plant parasitic nematode populations and in some cases increase the populations of plant parasitic nematodes[11], while a large number of authors have demonstrated that organic materials of plant origins were effective in suppressing plant parasitic nematodes[4,15,99]. However, their effectiveness on nematode population largely depends on method of application rates of application and quantity of plant-based materials used and rate of decomposition of the plant-based material. These factors should be considered when choosing and using plant-based materials as soil organic amendments to obtain better results[11].

Rate of application: Plant materials differ in the type of toxic substance(s) they possess and release during decomposition. Some produce substances that are highly toxic to the pests, while some produce those that are less toxic. Hence, it is important to identify the toxic compounds and their level of toxicity inherent in plant-based materials prior to usage. Lower rates of plant materials, containing highly toxic compounds should be used, while higher rates of plant-based materials with bioactive compounds with low toxicity levels should be used. In recent study, Amulu *et al.*[10] showed that leaf extracts of *T. diversifolia* were able to suppress the population of *Rotylenchulus* spp. at 40,000 ppm but failed to control the nematode when applied at 20,000 ppm. Based on their findings more concentrations of the plant extract are needed for better control of the nematode.

Rate of decomposition: The rate of decomposition can also affect the effectiveness of plant-based soil organic amendments used for nematode control. This is because some plant materials decompose and release nematode toxic compounds quickly; hence such plant-based materials should be preferred to those that are slow in decomposing. In addition, younger plants and plant materials obtained from younger plants or seedlings are known to be embedded with lower concentrations of cellulose materials, hence rate of decomposition is usually faster when compared with older plants or parts of plants obtained from older plants which are known to be characterized with high concentration of cellulose materials[121-123].

Methods of applications

Applications as cover crops or pre-plants: In this case, the plants are first grown on the field as cover crops and after a given period they are uprooted, chopped into smaller forms, incorporated into the soil and allowed to decomposed for some time before planting the main crop[4,20]. This method has been used by several authors in Nigeria and elsewhere and the results have been consistent in their effects on plant parasitic nematodes[4,8,12,122]. The uniqueness of this method of application is that the cover crops can suppress nematode populations while it is actively growing on the field by releasing allelochemicals that are toxic or antagonistic to plant parasitic nematodes and subsequently release of nematode-toxic metabolites following incorporation and decomposition[12]. A recent study by Amulu *et al.*[4] reported the effectiveness of this method. In their study two separate sets of field experiments were carried out in 2016 and 2017 to investigate the effects of sunn hemp and Mexican sunflower on yields of *Amaranthus cruentus* and *Solanum macrocarpon* grown in nematode infested fields. Eight week-old seedlings of sunn hemp and Mexican sunflower were worked into the soil at the rates of 10 and 20 seedlings per plot each at four weeks after transplanting. The results showed that plots treated with the cover crops at both rates suppressed the populations of plant parasitic nematodes and correspondingly increased the yields of the two vegetables compared with control plots.

Applications of plant residues as green manure: This is the most common method used in many African countries, it is the easiest and less time demanding; it involves the use of a variety of plant parts or residues for nematode management strategies. They are deliberately and directly worked and properly mixed with the soil for nematode control[123]. This method to a large extent has been reported to be effective in nematode management in the tropical and sub-tropical regions[111,112,123]. They also have dual effects in their effects on nematodes, in the sense that they suppress numbers of plant parasitic nematodes and also increase the yields of nematode infected crops[123]. The plant residues ranges from plant parts (leaves, stems and roots), kitchen wastes and restaurant wastes (yam peels, cassava peels, plantain peels, fruit peels, spoilt food and many more), agricultural and industrial wastes (sawdust, oil palm sludge). They decompose following incorporations thereby release all forms of natural substances some of which are highly toxic to plant parasitic nematodes. Neem leaves, cassava peels, yam peels, fruits peels and lots more have been reported to be effective on several nematodes including *Meloidogyne* spp., *P. brachyurus* and *H. multicintus* in most African countries[112,113,123].

Composted plant materials: This involves the use plant materials that have been allowed to decompose for a period of time for nematode controls[13,124]. In most cases, composted plant materials are prepared by mixing with animal manures to hasten decomposition. The advantage of this method over the other plant based method is that the natural chemical substances embedded in the plant materials are quickly and easily released into the soil for nematode control, following incorporation into the soil[13,124]. This is possible because the plant materials might have completely decomposed or at the process of decomposing by the time they are being applied to the soil[13,124]. Also the composted materials usually contain a host of microbial forms that are predatory to plant parasitic nematodes. They also have dual effects on nematodes and crop yields. Many plant parasitic nematodes including; *M. incognita*, *Helicotylenchus* spp., *Heterodera schachtii*, *Paratylenchus* spp. and *Pratylenchus* spp. have all been effectively controlled on a variety of crops with different composted plant based materials[13]. Ferraz and de Freitas[125] demonstrated the suppressions of *Paratrichodorus minor*, *M. incognita*, *Criconemella* spp. and *Pratylenchus* spp. following incorporations of compost on maize (*Zea mays*) in Florida, USA.

Application as plant extracts: The use of plants or plant-based materials in form of extracts for nematode control is gaining ground due to successes obtained by earlier workers; The preparations of these extracts differ and as such their efficacies differ and this depends on the best method used.

The concept of this method of nematode control strategy is based on isolating the active ingredient from plant parts and applied directly on the juveniles or eggs of the nematodes[9,10,29,40]. The bioactive substances are usually isolated from plant parts such as leaves, stems, seeds and roots, by dissolving them in a number of solvents ranging from ethanol and methanol to water and sometimes they are formulated into powder or oil forms[126]. The mode of action of this method is that the bioactive substances either delay or inhibits verse majority of eggs of the nematode from hatching or kill several numbers of juveniles of the nematode that hatched[30]. However, most study on the use of this method in nematode control are usually *in vivo* and *in vitro* experiments, hence the results need to be verified on the field before confirmation[11,104]. Recent data presented by Amulu *et al.*[10] on the effects of leaf extract of *T. diversifolia* on development and reproduction of *Rotylenchulus* on *T. occidentalis* under screenhouse conditions, showed that extracts of *T. diversifolia* applied at 40, 000 ppm significantly reduced the numbers and development of the nematode on *T. occidentalis* compared with untreated control plants.

Inter-cropping and crop rotation: The use of inter cropping or crop rotation strategy for management of plant parasitic nematodes focuses on the use of alternative host plants to either attract, interrupt or trap nematode pests which in turn reduces the damage they can cause on main crops[127]. This method involves the cultivation of more than one crop on the same field for nematode management. This is usually successful and effective when one of the crops can release allelopathic or nematode toxic compounds while growing or one of the crop plants is tolerant or resistant to nematode species[128,129]. This will create unfavourable environment that will affect reproduction and build up of nematode pests, thereby keeping their population below economic threshold. Several studies have reported toxic substances in the root zones of many plants which have been implicated in suppressing the populations of plant parasitic nematodes[127]. Adepoju *et al.*[49] demonstrated that intercropping yam with *Hibiscus sabdariffa* on field infested with *M. incognita* and reported that the *H. sabdariffa* reduced populations of the nematode and correspondingly increased the yields of *M. incognita* infected yam.

Plant essential oil: The plant essential oils are products extracted from aromatic plants. They are rich in secondary compounds and are complex mixtures that may contain several components in different concentrations. They are formed by a number of volatile substances which give them their aromatic small and chemical compositions[130]. Several studies have shown the nematicidal activity of many essential oils from different plants both in laboratory and greenhouse studies[53,131,132]. In a recent study, Adekunle *et al.*[133] investigated the effects of essential oils of *Artemisia absinthium*, *Mentha×piperita*, *Origanum vulgare* and *Thymus vulgaris* on *M. javanica* infecting tomato in a laboratory study. The oils were applied at 0.25 and 0.5% (v/v) and the results indicated that all the essential oils at both rates suppressed the population of the nematode. The application of z-β-ocimene and dihydrotagetone isolated from the oil of *T. minuta* at 4, 3, 2 and 1% exhibited strong nematicidal activity on eggs and second stage juveniles of *M. incognita*[134]. Also, Cetintas and Yarba[134] demonstrated that the application of essential oils of *Allium sativum* and *T. vulgaris* in soil, at 50 μL concentrations per plant, reduced gallings by *M. incognita* infecting tomatoes.

Factors affecting the effectiveness of plants and plant-based materials as soil amendment

Surface area of the plant residues/product: The surface area of organic matter is very important for the effective management of nematode populations. When the surface area is low, many of the nematode-toxic substances maybe locked up in plant tissues and as such may not be released on time. On the other hand when the surface area is high, the nematode-toxic substances are easily and quickly released from plant tissues. One way of increasing the surface area of organic materials is by chopping them into smaller pieces or forms[4]. The smaller or finer they are the more effective they would become on their actions against nematode pests.

Carbon/nitrogen (C/N) ratio of plant/plant based material: The rate of decomposition of organic matter depends on the carbon/nitrogen (C/N) ratio, as those with high C/N ratio decompose slowly in comparison with those of low C/N ration[11,135,136]. Plant parts have high C/N ratio because they are composed of cellulose cell walls, which contain slow decomposing compound (lignin)[121,137]. Hence plant residues obtained from plants with less lignin would decompose faster than those with higher lignin.

Age of plant residues: The age of plant or plant residues can affect the rate of decomposition and consequently the release of nematode-toxic substances following incorporation. An experiment conducted by Kato-Noguchi[138] on the effect of plant age at the time of mowing on sun hemp tissue decomposition, nitrogen release and fiber content were determined. The leaf and stem tissue from 42, 77 or 112 day-old sunn hemp plants were placed in bags and buried into the soil in the field. The bags were removed every two weeks and dry weights and nitrogen concentration amongs other data were taken. The result revealed that there was a fast decrease of plant tissue dry weight during the first 14 days after tissue was buried. The total concentration of nitrogen/hectare was lower for 42 day-old sunn hemp plant tissues in comparison with those of 112 day-old. They concluded that the tissue of the youngest plants decomposed faster and had a higher nitrogen concentration and nitrogen mineralization rate.

Soil conditions: The conditions of soil into which the plant residues are being incorporated are also very important. Soil pH, soil moisture and soil microbes are three important factors that can affect soil conditions negatively in relation to organic matter decomposition[4,8]. Soil microbes are responsible for organic matter decomposition. Inadequate soil moisture or the extremes of soil pH may affect their activities which in turn affects organic matter decomposition.

Concentration of phytochemicals in plants or residues: Plants are reservoirs of phytochemicals and many of these have been shown to be natural nematicides or nematode-toxic. Take for instance, neem leaves, siam weed leaves and siam weed roots which have been reported to suppress nematode populations were subjected to chemical analyses to ascertain the active ingredients in them. The results showed that neem leaves contain tannins and amines (methylamine); siam weed leaves contain alkaloids, flavonoids and amides (benzamide) and ketones (benzylethanone); while siam weed roots contain alkaloids, saponins, flavonoids, amides (benzamide) and ketones (benzylethanone an o-hydroxylbenzanone)[69]. Their numbers and their toxicity differ amongst plants, hence plants with more and highly toxic phytochemicals could be regarded as high in quality in their actions on nematodes Table 3.

Condition of plant residues or plant based materials: The conditions of plant residues prior to use as soil amendment is also important. Plants residues that have been fermented are more active or have their nematode toxic substances ready for action in comparison to unfermented plant residues. Also fermented materials are reservoirs of different microorganisms, some of which may be antagonistic to plant parasitic nematodes[13]. Fermentation of plant residues can be achieved by composting plant residues before used as organic amendment.

Mechanisms of plant parasitic nematode suppressions by plants and plant products: Amulu *et al.*[4] and Amulu *et al.*[10] have demonstrated the efficacy of plants and their products on a number of plant parasitic nematodes and to a large extent this approach has been successful. However, the mode of actions or mechanisms by which these plants and plant materials suppress nematode populations are not clear, but some authors have proposed that; allelopathic effects, release of nematode-toxic substances following decomposition, improvement of soil conditions amongst others are the major factors causing nematode suppressions[1,4,45,58,144].

Table 3: Nematode toxic (active) compounds present in selected plants and the nematodes they are effective against

Plant	Active compound (s)	Targeted plant parasitic nematodes	Reference
Sunn hemp	Monocrotaline	*Meloidogyne incognita*, *Rotylenchulus* and *Xiphinema*	Amulu *et al.*[4] and Thoden *et al.*[54] Amulu *et al.*[4],
Mexican sunflower		*Rotylenchulus* and *Meloidogyne incognita*	Amulu *et al.*[9], Amulu *et al.*[10] and Begum *et al.*[139]
Siam weed	1,2-dehydropyrrolizidine alkaloids	*Scutellonema*, *Tylenchorhynchus* and *Rotylenchus*	Adediran *et al.*[44] and Nawaz *et al.*[69]
Sudangrass	Dhurrin and sorgoleone		Chaudhary *et al.*[88]
Mucuna spp.		*Scutellonema*, *Tylenchorhynchus* and *Rotylenchulus*	Zasada *et al.*[90]
African marigold	α-terthienyl and bithienyl	*Meloidogyne incognita*	Adekunle[12] and Hooks *et al.*[27]
Sorghum	Dhurrin sorgoleone	*Meloidogyne incognita*	Adediran *et al.*[44]
Neem	Azadirachtin, Salannin, Meliantriol and Nimbin	*Meloidogyne incognita*	Nawaz *et al.*[69], Biswas *et al.*[94] and Martens[123]
Leucaena leucocephala	Ammonia	*Meloidogyne incognita*, *Pratylenchus* spp., *Paratylenchus* spp. and *Hoplolaimus*	Adekunle[15]
Lantana camara	Camarolic acid, lantrigloylic acid and triterpenes (pomolic acid), lantanolic acid and lantoic acid)	*Meloidogyne incognita*	Baba *et al.*[140]
Parkia biglobosa	alkaloids, saponins, tannin, flavonoids, phenol and glycosides	*Meloidogyne incognita*	Hamrita *et al.*[141]
Lemon grass			Oyedunmade and Izuogu[42]
Soybean	Ammonia		
Hibiscus sabdariffa	Hibiscus acid: 3-caffeoylquinic acid, 5-caffeoylquinic acid, 5-feruloylquinic acid, cyanidin 3-o-glucoside, myricetin, quercetin 7-o-rutinoside, quercetin 3-o-glucoside, delphinidin 3-o-sambubioside and kaempferol 3-o-p-coumaroyl-glucoside	*Meloidogyne incognita*	Adepoju *et al.*[49] and Khairy *et al.*[142]
Moringa oleifera	Saponins, flavonoid, glycosides and tannins	*Meloidogyne incognita*	Thoden *et al.*[143]

Allelopathic effects: In most African countries nematode diseases have not been devastating as compared in the developed countries of Europe and America. Reason partly due to the fact that there are many land areas covered with all kinds of weeds including; grasses, legumes, shrubs and trees in these regions. Most times farmers have to clear forests for cultivation of food crops and also cultivation of lands is not continuous making it possible for regrowth and redevelopment of the previous weeds. A large number of these plants may be releasing allelopathic substances, which constantly disrupt the life-cycle of plant parasitic nematodes, thereby, keeping their populations below economic threshold.

Allelopathic is the ability of some plants to release allelopathic substances via their root systems. These substances kill other plant seeds, preventing them from germinating, a mechanism which the plants use for competing with other plants for light, moisture and nutrients. Studies have shown that these substances are also toxic to plant pathogens including fungi, bacteria and nematodes[47]. One way to observe the allelopathic effects by plants is that such plants dominate on a field, fast growing and most times are less diseased. Amulu *et al.*[4] shown that several plants which exhibit allelopathic can be lethal on a number of pathogens including plant parasitic nematodes while actively growing on the field. Data presented by Amulu *et al.*[4] showed that the incorporation of sunn hemp and Mexican sunflower, after allowing them to grow on the fields for two weeks on fields infested with *M. incognita*, *Rotylenchulus* and *Xiphinema* planted to *Amaranthus cruentus* and *Solanum macrocarpon* suppressed the populations of the nematodes. However the authors did not take soil samples after two weeks or when the cover crops were still growing on the field, as this might have provided reliable information on the allelopathic effects on the nematodes. Never the less, sunn hemp has been demonstrated to release allelopathic substance known as monocrotaline while actively growing on the field[48]. This substance has been confirmed to be effective on *M. incognita*, *Rotylenchulus*[12,48]. On the other hand, Mexican sunflower has the potential to release similar substances. It is possible that the allelopathic substances released within the 2 weeks might have also contributed to the suppressions of the nematodes.

Production of nematode toxic substances during decomposition: A large numbers of plants have been reported to possess a number of natural pesticides, some of which have been reported to be nematode-toxic[69]. When the residues of these plants are worked into the soil, they gradually decompose and release nematode-toxic substances and when the concentrations of these substances are high enough, they become highly toxic and lethal to a number of plant parasitic nematodes. This fact has been confirmed by a number of authors[4,8,12]; Ogundele *et al*.[8] conducted a set of field trials to investigate the effects of African marigold and siam-weed, these weeds were completely chopped and worked into the soil as soil organic amendments to control *M. incognita*, *Helicotylenchus* spp. and *Dolichodorus* spp. infecting *A. cruentus* and *Telfairia occidentalis* and they reported that the soil amendments suppressed the populations of the three nematodes and increased the leaf yields of the two vegetables.

Modification and improvement of soil conditions: Plant nutrients are locked up in organic matters such as plants and plant based materials. These nutrients are released and made available for plant uptake following incorporation and decomposition of plant based materials[4]. The use of plant as green manure or cover crops is known to improve the fertility of soils[4,12]. Soils that are fertile facilitate fast and rapid growth and development of crop root systems and consequently increased growth and crop yields[145]. This is possible because crops cultivated in nematode infested fields might escape nematode attack or damage. Some data presented by Amulu *et al*.[4], Adekunle[12] and Germani and Plenchette[20] in their various studies all showed that plots treated with various plant and plant based materials produced healthy plants that had higher crop yields than those in control plots. Their results also revealed increased levels of total nitrogen, total nitrate, available phosphorous and exchangeable K in comparison with control plots. The increased plant nutrients might have enhanced the fertility of the soil which in turn might have facilitated the high yield recorded in the nematode infested plots. Additionally, the improvement of certain physicochemical conditions of the soil by the use of organic amendments has been shown to greatly influence the biological activities of the soil[4,136]. A comprehensive study on the effect of soil organic amendment on nematodes and soil properties have been reported by Amulu *et al*.[4], Adekunle[12] and Austin and Ballaré[136] . In their explanations; they maintained that the soil organic amendment improved soil structure, water-holding capacity and nutrient status and reduce weed growth which in turn benefited the plant health and resistance to the parasitic nematodes. Krupinsky *et al*.[145] added that this improved soil conditions might have helped the plants to ward off the attack of the parasitic nematode leading to suppression in their activities and populations.

Stimulations of antagonistic microorganisms: Plant residues ultimately becomes a substrate to a host of microbes when they are worked into the soil, this in turn increase their activities and numbers. A number of these microbes are antagonistic to plant parasitic nematodes. Increase in the populations of microbial organisms following the incorporation of organic materials including plant based materials has been reported by Akhtar and Malik[135]. In addition, the populations of free living nematodes are also affected by decomposing plant residues or plant based materials. In one of the data presented by Amulu *et al*.[4] showed that free-living nematodes including *Rhabditis*, *Dorylaimus* and *Mononchus* spp. populations were higher than those of plant parasitic nematodes in plots treated with either sun hemp or Mexican sunflower in comparison with those that were not treated with neither sunn hemp nor Mexican sunflower. They proposed that the high numbers of free-living nematodes in treated plots might have been facilitated by the sunn hemp and Mexican sunflower incorporated into the soil, which in turn might have led to the reductions of the populations of plant parasitic nematodes in treated plots. This proposal was confirmed by the findings of earlier authors who reported a negative relationship between free-living nematodes and plant parasitic nematodes in organic soils[146,147]. Free-living nematodes affect the populations of plant parasitic nematodes directly or indirectly[4]. The bacteria feeding nematode, *Rhabditis* affects the populations of plant parasitic nematodes negatively. As they graze on bacteria; they increase the concentrations of ammonia which is known to kill plant parasitic nematodes[58]. The feeding activities of Dorylaimus are known to deplete the populations of plant parasitic nematodes. As they feed on organic matter they facilitate its decomposition to release a number of substances from the organic matter and some of these substances are toxic to plant parasitic nematodes.

On the other hand, *Mononchus* spp. affect the populations of plant parasitic nematodes directly by preying on a number of them. They possess a teeth-like structure known as onchia which they use to rid plant parasitic nematodes apart. Blanchart *et al.*[147] reported higher populations of bacterial-feeding and predatory nematodes and lower populations of plant parasitic nematodes including *Criconemella*, *Scutellonema* and *Meloidogyne* spp., resulting from intercropping maize with *Mucuna pruriens*.

Activation of specific pathogen-antagonist micro-organisms: Certain plant species such as *Plantago* major and *Thymus officinalis* can release not only allelochemical compounds around their root zones but also harbours bacteria that are antagonistic to plant parasitic nematodes[148]. These bacterial isolates produce hydrolytic enzymes, some of which are chitinase, known to destroy the chitinous layer of nematodes and chitinolytic bacteria, which have been used as biological agents for nematode control[149].

Tolerance to plant parasitic nematode attack: Some plants can allow plant pathogens to penetrate them but refuse them from reproducing while inside the plant. Such plants are said to be tolerant to plant pathogens. Some many wild plants and weeds are known to be tolerant to plant parasitic nematodes and as such a large number them are used as trap plants to trap and disrupt the life cycle of plant parasitic nematodes. They allow the nematodes to penetrate the root system and the same time prevent them from completing their lifecycle. They do this by releasing nematode-toxic substances within the root system[128].

Trapping of nematodes by trap crops: The mode trap crops used in suppressing nematode populations has been reported by Scholte and Vos[150]. They attract plant parasitic nematodes away from the main crop, hence, by removing these crops from the field, nematodes would be indirectly removed before the end of their life cycle[127,151]. Additionally, some trap crops would perform as non or poor-host[129], while others would release a nematode toxic or allelopathic substances that inhibits nematode development or even kill them[27]. Other may produce metabolites that are lethal to nematodes[128] or are said to be "dead-end" trap crop, where eggs of nematode are triggered to hatch, then the juveniles would starve due to lack of a suitable host to live on[152] and a few would create the non-favourable environmental conditions for plant parasitic nematodes to thrive[153].

Activities of the nitrogen fixing bacteria (rhizobium) on leguminous plants: Leguminous plants are known to fix nitrogen into the soil by the aid of the nitrogen fixing bacteria, Rhizobium[48]. This substance mineralizes to form nitrogenous substances such as ammonium, nitric acid and nitrate. Ammonium ions or ammonia are known to be highly toxic to plant parasitic nematode[58]. Though authors are yet to confirm this fact, but it is possible it that it is one of the mechanisms nematode populations by leguminous plants.

Disruptions of the life cycles of plant parasitic nematodes: Soil organic amendments including those of plant and plant based materials affect the life cycle of nematodes thereby prolonging their generation time. They do this by delaying the hatching of nematode eggs as well as killing the second stage juveniles that hatched. Amulu *et al.*[4,10] reported that delayed reproduction, development and generation time of *M. incognita* and *Rotylenchulus* spp. following the application of water extracts of sunn hemp and Mexican and Mexican sunflower on *Solanum macrocarpon*, *Amaranthus cruentus* and *Telfairia occidentalis*, respectively. In an earlier study, Amulu and Adekunle[1] proposed that soil organic amendment can affect the sex ratio of *M. incognita* as they recorded more males of the nematode than the adult females in amended plants.

A combination of these and many more might be a salient explanation of how plant and plant based materials suppress nematode populations. More works are needed especially in the area of the use of leguminous plants as cover crops for nematode control. More expository research should also be carried out to know the extent to which the allelopathic substances affect nematode populations on the field while the plant is still actively growing.

CONCLUSION

A number of plants such as Sunn hemp, African marigold, Siam-weed, Mexican sunflower, Sudangrass, Velvet beans, Neem, *Leucaena leucocephala*, *Gliricidia sepium* and Agricultural wastes have been described to be reservoirs of natural pesticides. These plants and their natural pesticides have been tested on a number of plant parasitic nematodes and to a large extent have proven to be effective on their actions on plant parasitic nematodes. However, appropriate methods of application and the knowledge of the types of natural pesticides they contained will go a long way in their effectiveness when used for nematode management strategies. Additionally, the mechanisms by which plant and plant based materials suppress plant parasitic nematodes remain complex but the basic activities are decomposition and release of nematode toxic substances, allelopathic effects amongst others have been discussed.

SIGNIFICANCE STATEMENT

Plant parasitic nematodes are soil borne pathogens and can attack a number of cultivated crops causing yield losses. Control measures have been with the use of synthetic nematicides but they come with their drawbacks. Authors have suggested the use of plants and plant materials as plant parasitic nematode management strategy because of the promising results obtained. Unlike synthetic nematicides, natural nematicides from plants and plant based materials are easy to come by and are environmental friendly. The was done to reveal some important plants and plant based materials that have been successfully used for nematode management, various types of natural nematicides contained in some plants, methods of applying them to the soil and the mechanisms by which they control nematodes.

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