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Review

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Phytoparasitic nematodes as the major threat to viticulture

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Abstract

Grape plants (*Vitis vinifera* L.), like other major horticultural crops, suffer from attacks by plant pathogenic nematodes. These parasites are a serious burden for viticulturists all over the world and lead to reduced vine vigour and crop yield. The major nematode parasites infesting grapevines include *Meloidogyne* spp., *Pratylenchus* spp., *Criconemella* spp., *Tylenchulus* spp., *Helicotylenchus* spp., *Heterodera* spp. etc. Besides these genera, some nematode genera like *Xiphinema, Paralongidorus* and *Longidorus* are known to transmit viral diseases in grapevines, as they act as vectors to many viruses e.g. grapevine fanleaf virus. These pathogenic nematodes are becoming an important element affecting vine health, vigour and productivity. The present paper provides a brief overview of the diversity of phytoparasitic nematodes parasitizing vineyards, some viruses transmitted to grapevines via these parasitic nematodes and also outlines the management practices like crop rotation, hot water treatment, use of biological agents as well as use of organic amendments in controlling phytoparasitic nematodes in general.

Key words: grapevine, grapevine viruses, plant parasitic nematodes, plant protection.

Introduction

Nematodes are parasitic pseudoceolomic roundworms that feed on animals, plants, and other nematodes as well. Nematodes that parasitize different parts of a host plant are known as phytonematodes, phytohelminths, plant parasitic nematodes or simply plant nematodes, and the nematodes that feed on other nematodes are known as nematophagous nematodes. Nematodes are considered as one of the most ecologically diverse group of animals, ranging in habitat from the top of mountains to the deep oceanic sediments (Schratzberger et al. 2019). Phytohelminths are needlelike roundworms, except females of some species, which are pyriform or rounded in shape (Abanto et al. 2020). Plant parasitic nematodes are obligate parasites and in order to survive they must nourish themselves on the roots or the aerial parts (fruits, leaves, flower buds, etc.) of the host plant (Reddy 2008).

Throughout the globe, plant parasitic nematodes pose a major threat to almost all agricultural crops and it has been estimated that these parasitic nematodes are responsible for an annual loss of over US$ 358 billion globally (Abd-Elgawad, Askary 2015). The major genera of plant parasitic nematodes which lead to havoc to most important agricultural crops around the globe include *Meloidogyne, Tylenchulus, Helicotylenchus, Heterodera, Xiphinema, Longidorus*, etc. (Askary et al. 2018b). In India the estimated monitory losses to crops posed by all pests and diseases is approximately about 500 billion rupees (https://croplife.org/news/keeping-indias-pests-in-line/). The yield loss in the case of grapevines has been estimated to be about 12.5% on an annual basis (Sasser 1987).

The parasitic nematodes associated with grapevines usually damage below ground parts of vine, i.e. roots, and thus make them unable to meet the demands of above ground parts (McKenry, Bettiga 2013). Moreover, the injuries caused by plant parasitic nematodes on roots become prone to infections of other pathogens like bacteria, fungi, etc. leading to secondary infections (Walker 1995). A few phytoparasitic nematodes (less than 1%) act as vectors to viruses and thus lead to transmission of viral diseases in plants (Brown et al. 2004). Three major genera of plant parasitic nematodes viz. *Xiphinema, Longidorus* and *Trichodorus* are known to transmit viruses in different plants.

Globally, a wide variety of management strategies are being employed to lessen the damage caused by these microscopic creatures. Management strategies include cultural practices (like crop rotation, fallowing, flooding, destruction of roots after harvesting of crops, solarization, etc.). Application of nematicides is also a good option but is not an environment-friendly method in managing phytoparasitic nematodes. Nowadays more environment-friendly approaches, including the use of natural pathogens of phytoparasitic nematodes, application of plant based extracts, green manures, crop residues, composted yard material or animal manures, etc., are being employed in order to manage the populations of phytohelminths, which ultimately leads to increased productivity. The present review deals with updated data on plant parasitic nematodes parasitizing grapevines and also some of the strategies being employed in order to manage these pathogens.

Grapevines and their associated phytonematodes

Grapevine (*Vitis* spp.), belonging to family Vitaceae, is considered as one of the important fruit crops native to Asia Minor and the Caucasus region (Brown et al. 1993). It is a widely grown fruit crop around the globe and occupies nearly about 75 866 km^2 area of the world (Askary et al. 2018b) and it is estimated that nearly about 71% of the world grape production is used for wine production, 27% of the production is consumed as fresh fruit and approximately 2% of the fruit production is consumed in the form of dry fruit. In India the grapes are cultivated over an area of 117.6 thousand ha with annual production of about 24.831 million t (NHB 2013).

Grape is one of the most delicious fruit crops. It can be eaten raw or can be used for making wine, jam, raisins, grape seed oil, etc. The highest percentage of the grape production during 2005–2006 was shared by Italy (12.6%), followed by USA (10.5%), France (10.0%) and China (9.7%). In terms of productivity, India topped the list with productivity of about 25.4 t ha^{-1}, followed by USA with productivity of 7 t ha^{-1} (Kumar 2009). In India, most of the cultivated area (approx. 94%) falls in the tropical region (Pradeep 2006) and the major grape producing states include Maharashtra, Karnataka, Andra Pradesh and Tamil Nadu. Plant parasitic nematodes are considered to be the major threat of several grapevine growing regions of the world, as they cause reduced vine production and vigour (Pinkerton 1999). Although the grape fruit has pleasant aroma, taste, high economic as well as nutritional value, this fruit crop is attacked by numerous insect as well as non-insect pests, resulting in considerable loses annual

Plant parasitic nematodes are one of the major non-insect pests reported from almost all vineyards across the globe. Among the wide range of plant parasitic nematodes, the populations of *Meloidogyne incognita* are of worldwide concern and serve as a major biotic constraint to vineyards (Zasada et al. 2012). In India the estimated losses due to *Meloidogyne incognita* in terms of yield loss are approximately 30% and in terms of monetary loss – about 3940.44 million rupees (Kumar et al. 2020). Annual worldwide loss of grape yield due to nematodes is estimated to be 12.5% (Sasser 1987).

General life cycle of plant parasitic nematodes

A plant-parasitic nematode goes through six phases in its life cycle: egg, four juvenile stages, and adult. Most species are dioecious with both male and female nematodes, but some species are hermaphroditic and reproduce without males. The individual's egg production completes the cycle. Depending on the nematode species and their surroundings, most species generate between 50 to 500 eggs per female, although others can produce over 1000 eggs (Singh, Phulera 2015). The length of the life cycle differs significantly depending on the nematode type, host plant, and environment temperature. Many plant nematodes finish their life cycle in about four weeks during summer, when soil temperatures reach 27 to 32 °C (Singh 2000).

According to feeding habits, plant parasitic nematodes are classified as ectoparasitic, semi-endoparasitic, or endoparasitic (Palomares-Rius et al. 2017; Smant et al. 2018). Ectoparasitic nematodes spend their entire life cycle outside of the host, with only the insertion of a long and rigid feeding stylet providing physical contact. Semi-endoparasitic nematodes feed by penetrating roots and leaving the posterior part in the soil. Endoparasitic nematodes enter the root system entirely and feed on interior tissues. These feeding types are further subdivided into migratory and sedentary lifestyles. Migratory endoparasites (e.g., root-lesion nematodes *Pratylenchus* spp. and burrowing nematodes *Radopholus* spp.) travel through root tissues to feed on plant cells, causing tissue damage in the process. Sedentary endoparasites, on the other hand, travel into the vascular cylinder and cause host cells to redifferentiate into multinucleate and hypertrophic feeding cells (Sato et al. 2019).

Impact of nematode infestation on vineyard productivity

The phytoparasitic nematodes parasitize almost every agricultural or horticultural crop of the world and cause huge economic loses globally. Most people are usually unaware about these pathogenic parasites because of their microscopic nature and their presence within the soil. In terms of economic loss, the most important plant parasitic nematodes associated with grapevines are root-knot nematodes *Meloidogyne incognita, Meloidogyne javanica* and *Meloidogyne arenaria*. Some other phytonematode pests include lesion nematode (*Criconemoides xenoplax*), dagger nematode (*Xiphinema americanum, Xiphinema index*) and stubby nematode (*Paratrichodorus* spp. and *Namidorus* spp.) (Addison, Fourie 2008; Walker, Stirling 2008). These parasites usually feed on underground parts of vines and cause root malformations and necrosis (Nicol et al. 1999). Aboveground parts of grapevines usually show no specific symptoms but there is a general decrease in the vine vigour. Moreover, the injuries caused to plants due to penetration or feeding of these parasitic nematodes become prone to infections by other pathogens like *Phytopthora* spp., *Pythium* spp., and *Armillaria* spp. (Chiarappa 1959; Walker 1995).

Plant parasitic nematodes cause huge damage to crops, ranging from minor injury to total crop failure (Ravichandra 2014). The extent of the damage caused to crops depends on many factors, especially the severity of the infection. The estimated percentage losses by nematodes to grape crops is 12.5% (Sasser 1987).

Grapevine fan leaf degeneration is a devastating disease of grapevines caused by a virus that is transmitted through soil borne nematode of the genera *Longidorus, Paralongidous* and *Xiphinema*. Among these parasitic nematodes, *Xiphinema index* has the most significant impact on grapevine production, as it acts as vector to an important virus – grapevine fan leaf virus (Andret-Link et al. 2004).

A number of symptoms appear in a host plant when it is infested by parasitic nematodes. These symptoms are generally classified into two large groups: (1) above ground symptoms including chlorosis, stunted top growth, sparse foliage and (2) below ground symptoms including galls on roots, stunted root growth, necrotic lesions, and root rot.

Economically important genera of plant parasitic nematodes associated with grapevines

A number of genera of phytoparasitic nematodes are associated with the rhizosphere of vineyards across the world. Information on these parasitic nematodes available in the literature is presented in Table 1. It is evident that vineyards across the globe are susceptible to different nematode infections and the major genera of plant nematodes recovered from the infested soils are *Xiphinema, Meloidogyne, Longidorus, Pratylenchus, Criconemella, Tylenchulus*, etc. The data collected infers that the diversity and prevalence of plant parasitic nematodes infecting vineyards differs across several countries. For example, *Meloidogyne* is a common phytoparasite in India, USA,

Table 1. Diversity of phytoparasitic nematodes associated with grape vineyards

Country and area of study	Nematode genera / species found	Reference
Brazil, southern part	*Mesocriconema, Xiphinema, Hemicyclophora* were from vineyards, whereas *Meloidogyne, Pratylenchus, Mesocriconema, Helicotylenchus* were present in nurseries	Divers et al. 2019
Canada, Estrie and Monteregie	*Pratylenchus* and *Pratylechulus* were most prevalently found	Bélair et al. 2001
Chile	*Xiphinema*, *Meloidogyne*, *Mesocriconema*, *Tylenchus*	Aballay et al. 2009
Egypt	*Ditylenchus, Helicotylenchus, Hoplolaimus, Meloidogyne, Pratylenchus, Rotylenchus, Tylenchorhynchus, Tylenchus, Xiphinema*	Mohamed et al. 2017
Egypt, Ismailia Governorate	*Meloidogyne*, *Hoplolaimus*, *Tylenchorhynchus*, *Xiphinema*, *Pratylenchus*, *Rotylenchus*, *Helicotylenchus*, *Trichodorus*, *Criconemella*, *Longidorus*	Abd-El-Baset et al. 2013
Egypt, Minia Governorate	*Meloidogyne* (most prevalent), *Hoplolaimus, Longidorus* (low prevalence)	Hassan 2019
India, Coimbatore Tamil Nadu	*Meloidogyne incognita, Rotylenchulus reniformis, Helicotylenchus dihystera* were frequently found	Senthikumar, Rajendra 2005
India, Kashmir	*Tylenchorhynchus, Pratylenchus, Tylenchus, Rotylenchulus*	Askary et al. 2018a
Iran, Markazi province	*Aphelenchus avenae, Boleodorus thylactus, Pratylenchus neglectus, Helicotylenchus digonicus, Geocenamous brevidens*	Deimi et al. 2010
Iraq	*Xiphinema index, Xiphinema vuittenezi, Xiphinema diversicaudatum, Xiphinema pachtaichum, Tylenchus semipenetrans, Helicotylenchus pseudorobustus*	Stephan et al. 1985
Pakistan, Balochistan	*Aphelenchus avenae, Helicotylenchus indicus, Hoplolaimus indicus, Meloidogyne javanica, Meloidogyne incognita, Xiphinema americanum, Xiphinema index*	Khan et al. 2014
Spain, southern part	*Mesocriconema xenoplax, Meloidogyne incognita, Meloidogyne javanica, Xiphinema index, Xiphinema italiae* were prevalent species	Téliz et al. 2007
USA, California	*Achromadora walker, Criconemoides featherensis, Hemicycliophora armendae*	Al-Banna et al. 1993
USA, Georgia and North Carolina)	*Helicotylenchus, Mesocriconema, Xiphinema* were frequently encountered	Jagdale et al. 2019
USA, Washington and Idaho	*Meloidogyne hapla, Pratylenchus* spp., *Xiphinema* spp. were commonly encountered	Zasada et al. 2012
USA, Western Oregon	*Mesocriconema xenoplax, Xiphinema americanum, Pratylenchus* spp., *Meloidogyne hapla*	Pinkerton et al. 1999
Yemen, Sana'a and Sadah Governorates	*Tylenchus, Xiphinema, Helicotylenchus, Tylenchorhynchus, Rotylenchulus, Pratylenchus*	Mohamed 2009

Spain, Chile, Egypt and Pakistan, while the genus *Xiphinema* has been frequently observed in vineyards of Iraq, Yemen, Chile, USA, Brazil and Pakistan. Plant parasitic nematodes can be broadly grouped into four groups according to their mode of parasitism: (1) ectoparasites, which feed on the peripheral cells or the tips of roots and never enter into the root e.g., *Trichodorus* spp., *Longidorus* spp., *Xiphinema* spp.; (2) migratory endoparasites, which enter and move within the root and can leave one root to enter into a new one e.g., *Pratylenchus* spp.; (3) semi-endoparasites – their head usually enters the root while the rest body stays outside e.g., *Rotylenchulus* spp.; and (4) endoparasites, which enter and live within the root e.g., *Heterodera* spp., *Meloidogyne* spp.

The major phytoparasitic nematode genera reported to be associated with vineyards around the globe are *Meloidogyne* spp., *Xiphinema* spp., *Pratylenchus* spp., *Tylenchulus semipenetrans, Mesocriconema* spp., and *Trichodorus* spp. (Téliz et al. 2007; Ferris et al. 2013).

*Root-knot nematode (*Meloidogyne*)*

The root-knot nematode is the most common endoparasitic phytonematode, with worldwide distribution and responsible for severe economic loses globally. There are approximately 100 described species of *Meloidogyne*, of which nearly 50 species are known to be associated with the grapevines. This genera of plant parasitic nematodes is known to induce visible diagnostic symptoms on grapevine roots in the form of root galls, which result from hypertrophy and hyperplasia due to feeding of nematodes (Ravichandra 2014). The galls resulting from root-knot infection can be easily distinguished from those caused by bacteria *Agrobacterium vitis*, as the nematode galls are visible as thickenings of the entire root, especially on young feeder roots, whereas crown gall symptoms are seen on the side of older roots (Storey et al. 2017). One or several females are present per gall and each female may lay up to 1500 eggs within a gelatinous matrix on the root surface. Root-knot nematodes, besides infecting grapevines, also infect broadleaf weed species and cover crops if present within established infected vineyards. Under the mild temperatures in California, the Mediterranean Basin and South Africa, the three major species of *Meloidogyne* causing serious diseases are *Meloidogyne arenaria, Meloidogyne incognita* and *Meloidogyne javanica* (Lider 1960; Brown et al. 1993; Nicol et al. 1999; Anwar et al. 2000; Quader et al. 2001). However, in countries with a cooler climate, *Meloidogyne hapla* is the dominant species in South Australia (Stirling, Cirami 1984) and Eastern Washington (Howland et al. 2014). *Meloidogyne ethiopica* commonly infects grapevines in Chile (Carneiro et al. 2004), and *Meloidogyne chitwoodi* in California (McKenry, Bettiga 2013).

*Root lesion nematode (*Pratylenchus*)*

The genus *Pratylenchus* includes migratory endoparasitic species that live freely until they attain maturity and thereafter enter roots of the host plant, where they feed on cortical tissue causing extensive damage to the root system of the host plant/crop. This genus has a broad host range and is expected to infect over 350 plants (Ravichandra 2014). A number of species (*Pratylenchus vulnus, Pratylenchus neglectus, Pratylenchus pratensis, Pratylenchus scriber*, etc.) have been found to be responsible for reduced growth and yield in grapevines (Raski, Krusberg 1984) but the main species attacking grapevines are *Pratylenchus vulnus* (Allen, Jensen 1951) and *Pratylenchus zeae* (Graham 1951).

*Ring nematode (*Criconemella*)*

Ring nematodes include ectoparasitic species, which are found associated with the rhizosphere of major horticultural crops: peach, apricot, walnut, grapevine, etc. *Criconemella xenoplax* is a widely distributed species of this group, which feeds on cortical cells and root tips (Hussey et al. 1991). This parasite feeds on grapevine roots resulting in local darkening, destruction of roots and hence stunted growth of the root system. *Mesocriconema xenoplax* is widely distributed in vineyards of Eastern Washington (Howland et al. 2014) and is reported as the most common species in vineyards of Southern Spain (Téliz et al. 2007).

*Citrus nematode (*Tylenchulus*)*

This group of phytoparasitic nematodes has a narrow host range. They infest olive, grapevines and lilac in addition to citrus fruit trees. Being semi-endoparasitic in nature, their anterior portion of body remains embedded in root tissue, whereas their slender posterior portions of body remains protruded outside root tissue. *Tylenchulus semipenetrans* was first reported on grapevines in Australia (Seinhorst, Sauer 1956). When considerable populations of this parasite are associated with a particular host plant, they can cause a yield loss of about 13% (McKenry 1992).

*Dagger nematode (*Xiphinema*)*

The genus *Xiphinema* includes migratory ectoparasitic nematodes. About 163 species infect a wide variety of plants viz., strawberry, oak, rose, carrot, cherry, peach, corn, grapevines, some cereals, etc. The economically important species of this genus include *Xiphinema americanum, Xiphinema diversicaudatum, Xiphinema index, Xiphinema italiae*, etc. Dagger nematodes feed directly from root tips of grapevines causing enlargement or swelling of the root. Younger roots of woody plants are generally preferred by these nematodes. *Xiphinema americanum* reported from Oregon causes darkening and excessive branching of the root system of grapevines (Pinkerton et al. 1999). This parasite is also widely distributed in Australian vineyards (Walker, Stirling 2008). The genus *Xiphinema* is reported to be present in all major grape producing regions of the world like USA, Australia, and South Africa. Three species of dagger nematodes viz., *Xiphinema americanum, Xiphinema diversicaudatum* and *Xiphinema index* are commonly found in South African vineyards (Malan 1995). *Xiphinema index* is considered as an important phytoparasitic nematode, which serves as a vector for grapevine fan leaf virus. This virus is highly pathogenic causing abnormalities in shoots, leaves as well as berries and thus reducing the yield to a considerable level.

*Needle nematode (*Longidorus*)*

Needle nematodes are large migratory ectoparasitic phytonematodes with a broad host range. They possess a large odontostyle, by which they penetrate root cells and feed. Several species of genus *Longidorus* are reported from vineyards throughout the world viz., *Longidorus attenatus, Longidorus diadecturus, Longidorus iranicus, Longidorus macrosoma, Longidorus protae*, etc. (Ravichandra 2014). Some other pathogenic nematodes of grapevines include *Longidorus africanus, Longidorus elongates, Longidorus goodeyi, Longidorus magnus*, and *Longidorus diadectus*. The needle nematodes feed mostly at or just behind root tips and cause decreased meristematic activity as well as reduced root elongation. A few species of genus *Longidorus* serve as vectors of nepoviruses (Taylor, Brown 1997). The synergistic effect of nematodes and viruses results in extensive damage to infested vineyards. *Longidorus* is widely distributed from warmer to temperate regions of world (MacGowan 1982). In Bohemia and South Moravia (Czeh Republic) three species of *Longidorus* (*Longidorus elongates, Longidorus euorymes*, and *Longidorus leptoceplalus*) are reported (Kumari, Decreamer 2007). *Longidorus dialecturus* transmits Peach rosette mosaic virus to grapevines (Allen et al. 1982).

Phytonematode transmitted grapevine viruses

Vineyards are always targeted by a number of pests and diseases. One of the most serious diseases of grapevine is grapevine fan leaf degeneration disease, caused by a virus transmitted by the phytonematode family Longidoridae. The virus transmission actually takes place with the help of a specialized organ i.e. esophagus (Jonathan 2010). A large group of viruses is responsible for grapevine fanleaf degeneration disease, but only few of them are transmitted via phytonematodes (Brown et al. 2004): artichoke Italian latent virus, grapevine fanleaf virus, tomato ringspot virus, tobacco ringspot virus, strawberry latent ringspot virus, peach rosette mosaic virus, raspberry ringspot virus, tomato black ring virus, etc. Some viruses like grapevine fanleaf virus have narrow host ranges while other nepoviruses have a broad host range extending from small fruit crops, fruit trees to other cops like soyabean, tobacco, and ornamentals.

The primary symptoms of this disease are an abnormal primary vein pattern and widely open petiolar sinuses, thus resulting in fan shaped leaves, which gives the virus its name – grapevine fanleaf virus (Pearson, Goheen 1988). The infected vines also show yellowing of leaves in addition to shortened internodes and abnormal branching. The yield of berries is reduced to a considerable level, as nepovirus causes poor berry set and also results in numerous unfertilized berries (Andret-Link et al. 2004). The retention of nematode transmitted viruses may vary from 4 to 8 weeks (Raski, Hewitt 1960; Taylor, Raski 1964) to years (Esmenjaud et al. 2014). During the molting of juvenile stages of nematodes, the viruses are released, implying that neonate larvae are not viruliferous and that the viruliferous nature is generally attained again during feeding on infected roots.

General nematode management strategies

Nematode management is not and should not be a matter of simply identifying a specific nematode pest and then employing a chemical nematicide that is effective against it. There are a number of situations for which no safe, effective chemical nematicides are available. Most of the chemical nematicides are generally toxic and hence hazardous to environment as well as for non-target organisms including humans and beneficial microorganisms. Some of the nematode management strategies are discussed below.

Crop rotation

Crop rotation is one of the oldest practices used to reduce nematode populations or soil-borne problems. This management practice is usually helpful in the case of phytoparasitic nematodes or soil-borne pathogens that are host-specific – repeated planting a field with the same host crop/plant will enhance the establishment of that pathogen within the field. Thus, rotation to a non-host plant may interrupt the life cycle of nematode pest and allows natural mortality factors to reduce the populations of these pathogens (LaMondia 1999). Crop rotation for a period of three years can reduce nematode populations (Raski 1995). However some studies suggest that fields infested with *Xiphinema index* should be left fallow or rotated to a crop other than grapes or fig for at least 10 years (McKenry 2000).

Fallowing

Fallowing means leaving the land or a field as such i.e., with no plants on it for a sufficient period of time to starve the parasitic nematodes to death. In the case of grapevines, it has been suggested that there should be a gap of one year between the removal and replanting of vine, such that during this time gap nematodes will suffer from shortage of food and ultimately die due to starvation.

Hot water treatment

This practice is helpful in controlling phytoparasitic nematodes in grape planting material (Meagher 1960) and is commonly used in Australian vine nurseries. Although this practice has not been found to be highly effective against root-lesion and root-knot nematodes (Suatmadji 1982; Walker 1997), it has been utilized to control *Xiphinema index* on grapevine rootstocks by exposing rootstocks to hot water at 52 °C for about ten minutes. Similarly Meloidogyne spp. can be managed at varied temperatures i.e., 54.4 °C for 3 min, 50.0 °C for 10 min or 47.8 °C for 30 min (Ferraz et al. 2010). Hot water treatment was also recommended for controlling phylloxera on rooted grapevines in South Africa (Smith 1982). Phytoparasitic nematodes like *Meloidogyne javanica* can be eradicated when infested vines are immersed in water at 50.0 °C for about 15 min (Barbercheck 1986).

Chemical control

The chemicals that are used for controlling plant parasitic nematodes are grouped either as fumigants or nematicides based on their spectrum of activity. Fumigants have broad-toxicity effects, meaning that they affect many soil borne pests in addition to nematodes. Due to their phytotoxic effects, they are used prior to planting. However, this method eradicates nematode infections upto one meter depth and is not much effective for those crops that possess a deep root system (Lear et al. 1981). Fumigants in the form of sodium and dichloropropane are used in vineyards, but are expensive and require special equipment for their application in vine fields.

Nematicides, on the other hand, are generally specific in their nature of action by affecting only nematodes, thus having little or no impact other organisms like bacteria or fungi (Gunday, Kenrey 1977). The management of phytonematodes (*Meloidogyne* spp. and *Xiphinema index*) using chemical nematicides has been effectively practiced in established vineyards in California (Raski 1984; Radewald et al. 1987; McKenry 1992) and South Africa (Malan 1995). Due to the limitations of chemical nematicides, like unfavourable impact on the environment as well on non-target organisms, the use of chemical nematicides is prohibited in several countries.

Biological control

Use of biological agents like nematophagous fungi, bacteria, nematodes, etc. is another option for managing phytoparasitic nematodes. The efficiency of nematophagous bacteria and fungi against some plant parasitic nematodes, including root-knot and cyst nematode, has been well documented (Stirling 1991; Meyer 2003). It has also been documented that 323 nematode species are infected by parasitic bacteria like *Pasteuria* spp. (Chen, Dickson 1998). *Bacillus* spp. has shown promising effects on various phytoparasitic nematodes (Zhou et al. 2016; Rao et al. 2017).

Fungal parasites/pathogens of nematodes are grouped in two types: obligate and facultative. Obligate parasites such as *Catenaria* spp. and *Nematopthora* spp. infect nematodes via their spores, which usually adhere or enter the gastrointestinal tract of nematodes (Kerry, Crump 1980), whereas facultative parasites viz. *Dactyllela* spp., *Dactylaria candida*, and *Hersutella* spp. kill nematodes by trapping them (Hallman et al. 2009; Stirling 2014). Although biological control is an eco-friendly method, it has limited success (Sikora et al. 2008), as biological control products for nematode management are not available in market. The main drawback regarding their performance within fields is the survival and establishment of the parasites after their application.

Soil organic amendment

Fumigants as well as non-fumigants have a good nematicide potential, and are used in developed countries (Ansari, Khan 2012a; Ansari, Khan 2012b), but their negative impacts on the environment and non-target organisms have become a serious concern (Sparks 2003). Therefore, there is dire need to manage plant parasitic nematodes using environment-friendly methods and management using soil organic amendments is one of the best options. The different kinds of organic amendments used in managing phytoparasitic nematodes are classified into two types. Onsite produced amendment includes additives such as cover crops, green manure, crop residues, and oil seed cakes, which are incorporated in the soil. Offsite or exogenous amendment includes additives like compost yard material, animal waste or animal compost, which is transported from somewhere else into the fields (Mokrini et al. 2018; Ansari et al. 2019).

The addition of organic additives can decrease the infection or the population of plant parasitic nematodes directly by effecting soil properties or indirectly by improving plant growth, enhancing populations of antagonistic organisms (Rizvi et al. 2012a; Rizvi et al. 2012b; Tiyagi et al. 2011). The suppression in the population of parasitic nematodes of plants can be enhanced by utilizing the combination of soil amendments and solarization (Gamliel et al. 2000; Ferraz et al. 2010). Various proposed mechanisms have been known to cause suppression in parasitic nematodes of plants. For example, application of organic additives or amendments leads to increased activity of naturally occurring nematode antagonists (Akhtar, Malik 2000; Oka 2010). The nematicidal activity of different composts prepared from poultry, sheep, cattle and horse manure against *Meloidogyne incognita* caused a decrease in populations of root-knot nematodes associated with the experimental plant (Kerkeni et al. 2007).

Other advancements in phytonematode management

In addition to the methods discussed above, research has been done to test the nematicidal activity of various products derived from marine organisms. Among marine organisms such as seaweeds, sponges and cyanobacteria, seaweeds showed higher efficacy against plant parasitic nematodes (Veronico, Melillo 2021) and among the seaweeds, brown seaweeds showed the highest nematicidal activity (Paracer et al. 1987). An increase in the mortality of phytonematodes has been documented when soil was inoculated with endospores (Kumar et al. 1993) or extracts and exudates (Sharma et al. 2007). In addition, the effects of nanoparticles or nanoparticle loaded nematicides have been tested on phytoparasitic nematodes. A study was carried out to compare the efficiency of the bionematicide avermectin when used alone and in combination with nanoparticles composed of poly-γ-glutamic acid and chitosan. The mortality rate of nematodes treated with nanoparticle loaded nematicide was higher as compared to that of free avermectin (Liang et al. 2018).

Conclusions

Insight into the variety of phytoparasitic nematodes found in vineyard rhizospheres, as well as their detrimental effects on the health and vigour of this economically significant plant clearly indicates that the major genera that parasitize vineyards across the globe include *Meloidogyne, Xiphinema, Pratylenchus, Rotylenchus, Mesocriconema, Helicotylenchus*, etc. These parasitic species are continuously create a threat to almost every crop plant around the world, causing huge economic losses annually. The estimated monitory loss for grapevines due to *Meloidogyne incognita* in India was about 3940.44 million rupees during 2014–2015 (Kumar et al. 2020). Literature suggests that some parasitic nematodes act as vectors of nepo-viruses, and in order to combat the negative effects of these parasitic nematodes, different management practices are employed. Among management strategies, chemical nematicides have considerable negative impact on populations of plant parasitic nematodes, but have side effects. Therefore, one should focus on management utilizing eco-friendly approaches like use of biocontrol agents, resistant cultivars, and application of organic amendments to the soils. Emerging evidence suggests that products derived from marine organisms have potential nematicidal effects (Veronico, Melillo 2021), but there is a need for further work to be able to control the parasitic nematodes associated with vineyards in order to increase the productivity of this fruit crop.

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