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Root-knot Nematodes: AWake-up Call to Rescue Crops in Africa from*Meloidogyne incognita* and its Allies

A. M. Ajayi
Department of Crop, Soil and Pest Management. Federal University of Technology, Akure, P M B, 704. Akure, Ondo State, Nigeria

Abstract: *Root-knot nematodes are invertebrate worms that belong to the genus Meloidogyne. Over 90 species have already been described, several of which are known to be parasitic on plants. They are reported to be one of the most devastating groups of worms, in terms of the damage they cause to crops, resulting in global crop failure and yield loss estimated to be several millions of dollars annually. This review focused on the devastation caused by these worms to crops and crop production in Africa. Their socio-economic impact is examined on a crop by crop basis, with appropriate data where applicable, across the length and breadth of the continent. The biology, life cycle, infestation process and mechanism of damage of Meloidogyne spp. to crops is examined carefully, while the various management options available are discussed critically one after the other, with specific examples of successes achieved. Special emphasis is laid on the suitability and practicability of each management option in rural and less than ideal condition under which farming occurs in most African communities. The peculiarities of farmers and farming in the continent are also highlighted. This is to ensure that only management options that are suitable, sustainable and with the best chance of success are considered for adoption in any management program that may be design to tackle the problem.*

Keywords*: Root-knot nematodes, crop failure, yield loss, Africa, management options*

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I. Introduction

Nematodes are in the phylum Nematoda. They are round and unsegmented worms with a worldwide distribution spanning diverse habitats. Some live freely in the soil, while others are parasitic with a wide host range, including humans, animals and plants. Nematodes that infest plants are called plant-parasitic nematodes (PPN). PPN, the focus of this review, are found active and abundant in most moist garden soils, inhabiting the top0 – 15 cm.The dormant and resistant stages of PPN can remain inactive in a dry and inhospitable environment for a long period. PPN has different sizes and morphologies but majority appears round and tappers at both ends. Motile nematodes move from one point to another through contraction of muscles that results in a characteristic motion called sinusoidal movement. Two groups of PPN, the cyst and root-knot nematodes, have attracted immense attention from plant pathologists. This is because of the serious damage they cause to crops. Cyst nematodes belong to the family *Heteroderidae,* which consists of at least six genera. They appear vermiform at certain stages in their life cycle, during which they are structurally different from other PPN[1]. The root-knot nematodes (RKN) are the most devastating in terms of the damage they cause to crops, the monetary values of these damage run to several millions of dollars annually[2]. They belong to *Meloidogynidae* family and *Meloidogyne*genus with over 90 species[3]. RKN thrive in places with warm temperature[2] and the climatic condition in most African countries suit them perfectly. Almost all known staple crop in the continent is susceptible to one species of *Meloidogyne* or the other. Poor plant growth, loss of vigour, susceptibility to infection from pathogenic microorganisms, poor yield, quantity and quality,loss of revenue and poverty are some of the consequences ofRKN attack. *Meloidogyne* spp. are a serious threat to food security in Africa, and there is anurgent need to find and adoptsuitable management options that will halt the current wave of infestation across the continent.

II. The root-knot nematodes

2.1 Classification, distribution and morphology

RKN belongs to the Phylum Nematoda, Order: Tylenchida, Family:Meloidogynidea and Genus: Meloidogyne. Reports from literature suggest that over 90 species of RKN exists[4]. They are found all over the world under different climatic conditions but are particularly best suited for a warm climate. Their presence has been reported in several African countries.*M. incognita* (Plate 1a) is the most commonly encountered root-knot nematode in most African countries. It exhibits sexual dimorphism with the female being distinct and easily distinguishable from the male. The female has a soft globose body that may be 0.4-1.3mm in length and that terminates in vulva and anus. A short stylet occurs anteriorly with a small basal knob. The ovary is conspicuous and occupies most of the body cavity. It produces eggs which are laid in egg sacs produced from the rectal glands. A characteristic circular marking usually found in the perineal area is an important identification tool for female *M. incognita*. The male, on the other hand, appears long and thin with a cylindrical body. The stylet (plate 1b) is also shorter and less robust than for other species of *Meloidogyne*. One or two testes are present, producing spermatozoa, while phasmids occur very close to the cloaca. The spicules appear a little curved.

Plate 1a.*Meloidogyne incognita.* Source: Rui MapZheng. Budwood.org

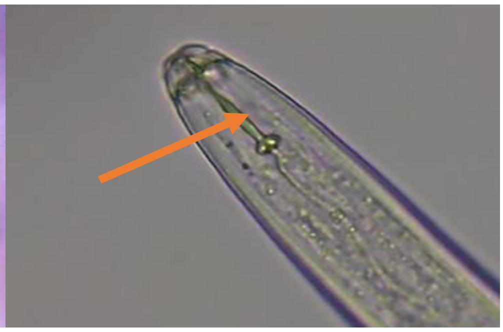

Plate 1b. Stylet of *M. incognita*. Source: www.flickr.com/photos/scotnelson/39895394551/in/photostream/

2.2. The life cycleof Root-knot nematodes

The life cycle of a typical RKN is simple, consisting of 4 juveniles and the adult male and female. The female produces hundreds of eggs which develops into new nematodes after fertilization. In some cases, however, new nematodes may be formed without fertilization, a phenomenon called parthenogenesis. The eggs are expelled in a mass from the female body and rapid development occur within each egg shortly after laying, leading to the production of the first stage juvenile (J1) after moulting. Each egg then hatches and moult the second time, giving rise to a fragile but motile second stage juvenile called (J2). The J2 is the infective stage and are attracted to and move towards host plant roots. Each J2 infest a host, moults a few more times and becomes the adult. The adult female then formsnew eggs and lay them, with or without fertilization and the cycle is repeated with the infestation of new root hairs on the already infested host or on a new host (Plate 1c). The time it takes for one juvenile stage to moult and develop into the next and for the entire life cycle to be completed is dependent on the species of RKN, the host and environmental factors (Plate 2a).

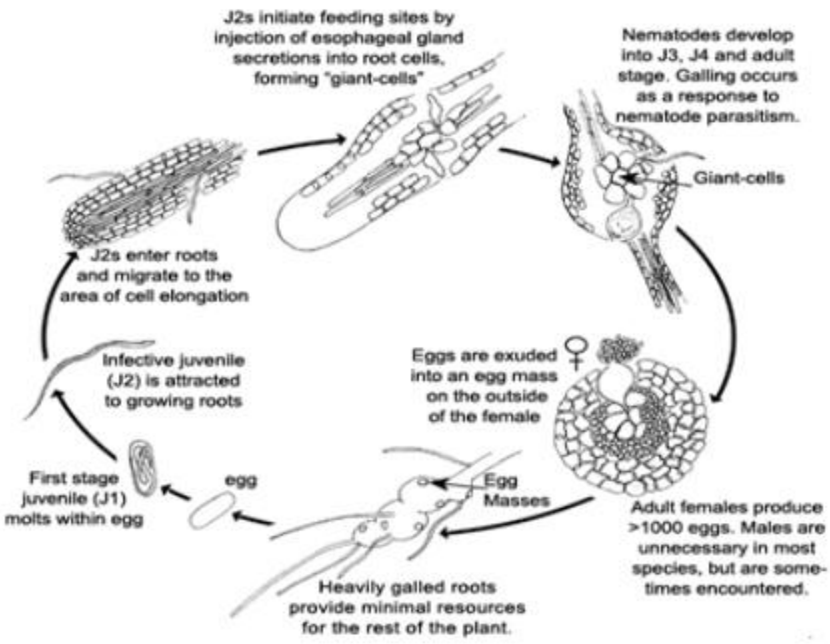

Plate 1c. The life cycle of a root-knot nematode. Source. Mitkowski and Abawi (2003)

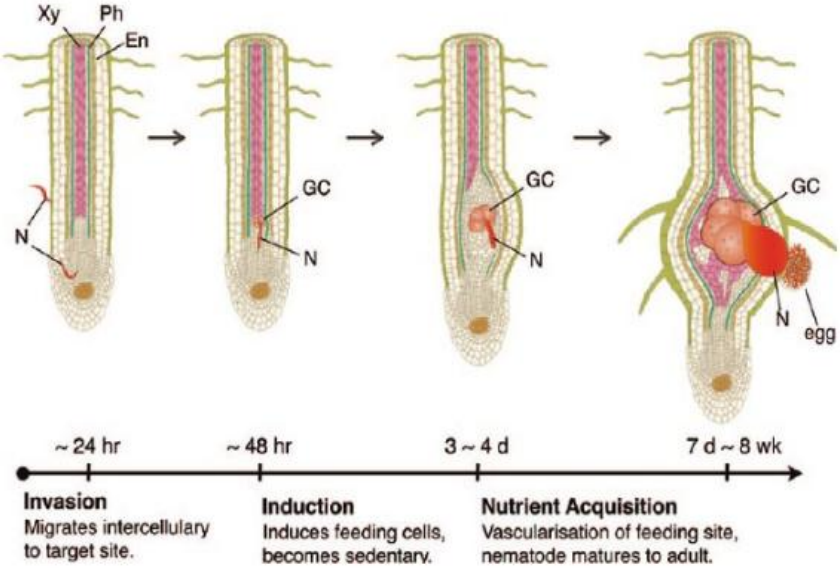

Plate 2a. Infestation process in a root-knot nematode. Source: Bartlem *et al.* 2013.

2.3. Host range, and economic implication of root-knot nematode infestation on Africa's staple crops.

A wide range of Africa's staple crops is host to one or more member of the Meloidogyne genus. Root and tubers, fruits and vegetable, legumes and pulses, cereals, oil crops and several others have been reported to suffer varying degrees of infestation. Increased cost of production, delayed maturity of crops, poor quality and quantity of yield, hunger and loss of income amounting to several millions of dollars annually are some of the consequences of nematode attack on these crops.

2.3.1 Root and tubers

A survey was conducted on the incidence of RKNon yam (*Dioscorea*spp.)in Nigeria and Ghana. The result was shocking as several tubers were found to be infested. *M. incognita* was the most commonly isolated from infested yams, accounting for 69% of infestations, followed by *M. javanica* with 13%. *M. enterolobii* and *M. arenaria* had 2% of incidence each[5]. The incidence of *Meloidogyne* spp. on yam has also been reported in Uganda where *D. rotundata*is the most susceptible[6]. Infested yams developswellings, resulting from giant feeding cells within the yam tissue, and the disruption of the physiological activities of the cell owing to the presence of the infesting nematodes. Dry rot and cracking of tubers may also result. Severe infestation can make tubers unfit for consumption, while moderate infestation can lead to loss of aesthetic value and a reduction in the market value.Rapid loss of weight in storage and reduced viability of yam seed/settare some of the other associated consequences of RKN infestation[6]. *Meloidogyne* spp. are also known to infest cocoyam and potato cultivated in the continent. *M. incognita*, *M. arenaria*, *M. hapla* and *M. javanica* have all been linked with the infestation of these crops[7].

Cassava (*Manihot esculenta*) is a household crop that is cultivated in most Sub-Saharan African countries. The tuber can be eaten fresh, after boiling, or as a component of vegetable salad. It can also be processed into powder, chips, flakes to mention a few. This utility crop is also under threat from RKN.Ekine*et al*.[8] found *M. incognita* to be the most dominant nematode associated with cassava in Rivers state, Nigeria. Coyne *et al*.[9] reported on the prevalence of *Meloidogyne*spp. in cassava farms in east Africa, causing galling, damaging cassava roots and bringing about poor harvest. In an experiment conducted in Uganda, Makumbi-Kidza*et al.*[10] found that *M. incognita* significantly reduced storage root formation and brought about a decrease in its weight. The infestation of cassava usually occurs at the early stage of storage root formation, resulting in the malformation of already formed roots and prevention of the formation of new ones. The implication is that fewer tubers are produced, while those formed are small in size with distorted shapes.

2.3.2. Legumes

Cowpea(*Vigna unguiculata*) is one of the most commonly cultivated legumes in Africa. It is a rich source of protein for many poor Africans that find other sources too expensive. Unfortunately, cowpea is also not spared by RKN.*M. incognita* is the most serious nematode of the crop in the continent, causing major yield and economic losses[11]. Sawadogo *et al.*[12] surveyed cowpea for associated PPN in Burkina Faso. Twelve generawere identified, but Meloidogyne was one of the three found to be of significant importance in disease development.

In South Africa, *M. incognita,* M. *Javanica, M. Arenaria* and *M. hapla* are all known to infest soybean (*Glycine max*), but *M. incognita* is the most devastating, resulting in 9% to 100% yield loss[13].

African yam bean, (*Sphenostylisstenocarpa)* is another very important legume grown in West Africa. Its protein content is very similar to that of cowpea and may be up to 29% in some cultivars. In Nigeria, a significant reduction in the growth and yield of the crop, as a result of *M. incognita* infestation has also been reported. Yield loss of up to 74% was reported in susceptible varieties[14].

In another study to evaluate the level of susceptibility of 12 crops commonly intercropped with yam in Nigeria, *Arachis hypogeal* and *Cucumis melo*were also found to be under threat from nematode attack. It was reported that both crops ware hyper-susceptible to *M. incognita* race 2[15].

2.3.3. Fruits and vegetables

Many cultivated fruits and vegetables in Africa have shown susceptibility to PPN. Seven leafy African vegetables were evaluated in the nursery and field in Kenya. Findings showed that *Meloidogyne* spp. caused considerable damage to these vegetables both in the nursery and field, with conspicuous galling, which prevented the proper establishment of the seedlings and brought about low yield[16]. A similar study reported80 - 100% yield loss in these vegetables[17].

Avery high frequency of occurrence, 86.5%, and a high disease incidence,measured in terms ofgall index (GL) and egg mass index (EMI) of RKN on tomato (*Lycopersicon esculentum*) was reported in Eritrea in 2011. The report also indicated a wide distribution of RKN in different parts of the country, posing a serious threat to the cultivation of other crops like chili pepper, okra and spinach, amongst others, that are susceptible to the worms[18]. In a survey conducted in Makurdi, a popular town noted for tomato cultivation in Nigeria, between 2010 and 2011, the incidence of RKN on tomato was found to be from 20 – 80%, while severity was from 1-4, in a 1-5 rating scale[19]. It must be pointed out that RKN attack on tomato is not new in Africa. Several years ago, a report of the destruction of a tomato field in Ghana, owing to the attack of RKN was reported[20]. A similar scenario was reported in a vegetable field in Kenya a few years later[21]. One thing both cases had in common was that the fields were previously uncultivated. Infestingnematodeswere suspected tohave survived on weeds and volunteer crops. This is a pointer to the great diversity of hosts and adaptabilityof RKN in Africa.

In Morocco, *M. javanica*is reported to be a major problem confronting banana and plantain production[22].Report from Cameroon points to the fact that attack from RKN is responsible for the toppling of banana and plantain. This results in the loss of bunches and an overall annual yield loss of about 60%. Most farmers have either stopcultivating the crop or restricted it to one season, this is because infestation and yield loss increases with subsequent season after the first[23].

2.3.4. Grains and cereals

Sorghum (*Sorghum bicolor*), millet (*Pennisetumglaucum*), maize (*Zea mays*) and rice (*Oryza* spp.) are some of the common grains and cereals cultivated in Africa. These crops are all not spared from RKN attack. Records of incidence and severity of varying degrees have been reported for them across the continent. In1998, *M. javanica* and *M. incognita*were reported to be major nematode pathogens of maize in South Africa[24]. The infestation of RKN on maize roots is usually subtle and maybe unrecognizable sometimes, owing to the smaller size of galls, in comparison to other crops. This does not, however, diminish its devastation as serious losses can be incurred. In Nigeria, yield loss in maize infested with RKN have been reported to be above 50% in some cases[25].

Millet (*Pennisetumglaucum*) is believed to have sub-Saharan Africa as its center of diversity and is widely cultivated in the arid savannah regions of the continent. While some cultivars of the crop are known to be exhibit resistance to RKNothers, especially those cultivated in some west and east African countries, are susceptible[26].RKN, especially *M. incognita* have been reported to cause huge annual yield loss of rice among peasant rice farmers in Kenya[27].*Melodogyne* spp. Also, infest rice in west Africa. The prevalence rate has been put at 50%[28] with serious implication on crop productivity.

2.3.5. Tree crops

Tree cropsare also known to be susceptible to RKN attack. For some of these crops, infestation starts in the nursery. For others, however,it starts shortly after transplanting, a period when seedlings are young, fragile and highly susceptible.Infested seedlings have a poor establishment, leading to loss of planting materials and additional cost to supply or manage weeds that grow freely where seedlings fail to establish.

Cocoa (*Theobroma cacao*) is an important cash crop for some African countries, especially in the West Africa sub-region. Over the years, the productivity of the crop has declined, bringing about reduced foreign exchange earnings for the government, increased poverty and poor quality of life among cocoa farmers.

Infestation from RKN, amongst other factors, is responsible for the decline in productivity. Ten cocoa clones were evaluated for tolerance to RKN in a field infested with *M. incognita*in Nigeria. Five of the clones were found to be susceptible, two were tolerant while only three exhibited resistance[29].

Coffee (*Coffea arabica*) is another very important cash crop in the continent. Ethiopia, Uganda, Rwanda, Tanzania and a host of other countriesgrow the crop. Sadly, coffee is also not spared by RKN.*M. Africana* and *M. decalineata*[30]are the two species of RKN that are known to parasitize the plant. They are widely distributed in the coffee-growing countries, especially Tanzania, Zaire and Kenya. Infested coffee roots have poor water and nutrient absorption, leading to poor plant growth and coffee yield.

Cashew (*Anacardium occidentale*) is cultivated widely across the savannah belt of Africa. The fruits and seeds of cashew are very important industrially, and the crop provides a means of livelihood for millions of African households. The wide-spread distribution of plant-parasitic nematodes in the cashew growing region of north-central Nigeria and the susceptibility of the crop to RKN, especially *M. incognita* has been reported[31]. The young seedlings are particularly the target of the pathogen. Infested cashew seedlings exhibit stunted growth and leaf yellowing.

The effect of RKN on several other crops grown in the continents have been reported, it appears no species, variety or cultivar is safe. Unfortunately, most farmers in rural Africa have poor knowledge about the presence of these worms.

III. Infestation process and pathogenesis of RKN on susceptible crops

The second stage juvenile, J2, is usually the infective stage of mostRKN. At this stage, the young nematode moves towards and make contact witha root hair. It thenpierces the protective layers of the cell with its sharp and protrusible stylet. This attack usually occurs in the region of active cell elongation (Plate 2a).The infecting juvenile produce and release secretions from its gut to the infested root tissue. This secretion aids its feeding and the breakdown of cells in the infested region. The J2 nematode then travels, intercellular, towards the tip of the infested root, pushing the cells apart and causing the breakdown of the middle lamella and the eventual collapse of the cellular frame-work of the infested region. The destination of the infesting nematode is the vascular tissue, where feeding sitesare established. Collapsed cell are converted to feeding zones, leading to the formation of small swellings (Plate 2a). The Infesting nematode molts and matures as it journeys through the root. The female becomes laden and swollen with egg mass. The eggs hatch to produce new sets of J2 juvenile. These migrate to and re-infest already infested root or find new ones. This cycle is repeated over and over again until several roots become infested. The result is extensivedistortion of the entire rooting system, giving rise to giant galls or tumours (plate 2b). The gallscontain abnormal plant cells, nematode's eggs and juvenilesat various stages of development and adult worms. Proper absorption of water and mineral salts through the vessels of the xylem tissues is hindered. The translocation of manufactured food, assimilates, beyond the infested, galled, portion through the sieve tube of the phloem tissueis also prevented[32-34].The host plant reacts to the presence of the pathogen with its secretions and with morphological and physiological changes that may manifest below or above ground with varying degree of severity.

Plate 2b. Root galls resulting from root-knot nematode infestation. Source: www.dengarde.com/gardening/Why-Are-Nematodes-Hurting-Your-Plants

3.1. Symptoms of root-knot nematode attack on crops

The openings created through piercing and penetration by the second-stage juvenile, J2, serves as an entry point for secondary infection from pathogenic microorganisms. Also, the poor absorption of water and mineral salts, as well as the little or non-availability of assimilates in certain parts of the plant, results in poor vigour. Plant with poor vigour are less competitive and are more susceptible to infection.Records show that infestation from RKN causes a breakdown of resistance in resistant varieties of crops[35].Consequently,crops under nematode infestation may manifest several symptoms, some of which may not be directly connected with the infesting nematodes, but maybe the result of infection from one or more pathogens or a disease complex. There is always a need to examine the roots/rhizosphere of crops suspected to be under RKN attack before confirmation can be made. Symptoms characteristics of RKNinfestation are usually divided into two

3.1.1. Above-ground symptoms

i. Small-sized leaves and reduction in the total number of foliage
ii. Wilting and death of host plant
iii. Patchy stunted growth with short internodes, reduced branches and weedy appearance
iv. Shoot dieback in perennial crops often preceded by scanty leaves
v. Poor nutrient uptake resulting in nutrient deficiency symptoms even after the application of fertilizer
vi. Increased weed population resulting in increased cost of weed control, because infested crops are less able to compete with weeds
vii. Fewer fruits with small size are produced.

3.1.2. Below-ground symptoms

i. Root deformation
ii. Roots may become necrotic, rot or dies
iii. Root galling of different dimensions, ranging from small bead-like swellings, swollen root tips, clumped fleshy tissue to a massive tumour. Depending on the species of RKN, the host and the stage of infestation.
iv. Formation of extremely short roots with poor absorption ability
v. Root and tuber cracking

IV. Management of Root-Knot Nematodes

If success is to be achieved in the management of RKN, farmers must be educated about plant-parasitic nematodes and the need for prevention of infestation should be emphasized.Prevention is cheaper and easier than the application of any control strategy. Prevention can be achieved by ensuring that only healthy planting materials are used for propagation. Planting should not be done on RKN infested field, just as the movement of soils from such fields to healthy ones should be prohibited. Hoes, cutlasses, tools and other farm implements that are used for tilling the soil must be cleaned of soil lumps, washed and disinfected after use. Strict quarantine regulations should also be observed to prevent the introduction of infested seeds, seedlings or crops. A lot of farmers in rural Africa knows little or nothing about PPN, they need to be educated.In communities where a good knowledge of RKN exists and among elite African farmers, the use of synthetic chemical nematicide is the most common response to infestation. The high cost of these chemicalscan be a major problem. It is worthy of note also that Africa has become a dumping ground for expired, substandard and adulterated agrochemicals, nematicides inclusive. Consequently, the desired result may not be achieved after use, this is in addition to the very high level of toxicity of these nematicides.

4.1. Planting of Marigold

Tagetes spp. (Plate 3a), popularly known as marigold or wild marigold are known to be natural antagonists to RKN. The roots of the plant produce exudates which are toxic to Meloidogyne and several genera of PPN[36]. The mode of action is allelopathic in nature. All a farmer need do is plant marigold at strategic locations on the farm, like what is obtained in a mixed cropping system. The distance of marigold from crop plants and required spacing can be determined in collaboration with experts in the field of nematology. Several active compounds in marigold have been isolated and identified, including 5-(3-buten-1-ynyl)-2,2-bthienyl, which is known to suppress nematodes, phenols, amines, ketones amongst others. Interestingly, certain species of the plant are also known to possess anti-fungal, anti-bacterial and insecticidal properties[36].*T. patula* (French marigold) and *T. erecta* (African marigold) have both been used against root-knot nematode of tomato with impressive results[37,38].

4.2. The use of plant extracts

Several species of plants all over the world are known to possess medicinal value against common ailment in humans. Research has also shown that some of these plants possess antimicrobial properties against plant pathogenic organisms[39,40], including PPN. Extracts from 5 plant samples were found to exhibit complete inhibition on egg hatching and mobility of J2 juvenile of *Meloidogyne* spp.*in vitro* in Turkey[41]. The *invivo* evaluation also brought about significant improvement in the growth and performance of tomato in the green-house. A similar finding was reported on *M. incognita* of cucumber with the use of extracts and essential oils from Castor bean, Chinaberry and Rapseedin an *in vitro* and *in vivo* study carried out in Iran[42]. Results showed that extracts from Chinaberry and Castor bean had significant inhibition on the mobility of J2 juvenile in the greenhouse. Waweru *et al.*[43]evaluated Sodom apple fruit extract against the root-knot disease of Chili pepper caused by *Meloidogyne* spp. in Kenya. It was reportedthat the extract has potential as a management option for the disease.In Nigeria, neem and groundnut leaves, as well as garlic bulb extracts, were evaluated against the larvae of *M. incognita*[44]. Neem and garlic extracts had significant inhibition on *M. incognita* and brought about increased growth and performance of tomato. These findings all points to the immense potential inherent in plants extracts as a management option for RKN. The large population and diversity of these plants in Africa make them extremely relevant. Species found to possess nematicidal properties can be applied as mulch material or may be ground to powder, after air drying, and applied into the soil close to plant stands. This practice will not only manage RKN, but will also improve soil fertility and other physio-chemical properties.

Plate 3a. Marigold plant (*Tagetes erecta*) Source: www.shutterstock.com/video/clip-15857038-marigoldtagetes-erecta-mexican-marigold-aztec-african.

4.3. Soil solarization

Soil solarization aims to increase soil temperature to a point where soil-borne pathogenic organisms, as well as weeds and their seeds, are killed or weakened. This is achieved with the use of polythene sheath to harness solar radiation. The polythene sheath, which may be black or transparent, is laid on moist soil while the edges are buried or closed up firmly with rows of balls of earth (Plate 3b). Heat and radiation from the sun are trappedby the laid-out polythene. This brings about a gradual increase in the temperature of the covered soil until it becomes lethal to organisms within it. The best time to carry out soil solarization is during periods of long hours and more intensity of sunshine. The duration of coverage varies, depending on the objective, but may range from 4 to several weeks. The thickness of the polythene is also very important as it determines the effectiveness or otherwise of the entire process. Efficient heat transfer is achieved if the soil is moist, hence there may be the need to irrigate soil before and during the solarization process.

African is blessed with lots of sunshine, a warm temperature almost all the year round and two distinct seasons, raining and dry. Solarization can be used almost all the year-round, but the best result will be achieved if used during the dry season. The duration of the solarization process is very important, as an increasing number of days has a direct correlation with a reduction in the population of RKN. This was confirmed by[45], who found that a 30 days solarization period with the use of 5 mm thick polythene not only brought about a significant reduction in the number of RKN and galling associated with tomato in a teaching and research farm in Ghana but also suppressed the growth of some common weeds. Solarization, as the sole treatment, was also found to reduce the incidence of galling induced by *M. javanica* in an organic farming system using a pot and field experiment[46].

Plate 3b. Soil solarization with transparent polythene. Source: www.ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=30435

4.4. Soil amendment

Soil amendment, especially with organic manure, has been reported to have some controlling effect on the population of soil-borne nematodes. Some authors found the effectiveness of such organic manure to be enhanced if used in conjunction with plant products[47] and urea[48]. A minimal reduction in root-knot index of*M. incognita* on tomato was recorded when fresh cow dung was used as a soil amendment[49]. Pig excrement brought about significant growth in African yam bean with enhanced tolerance to *M. javanica* infestation and suppression of root gall and egg mass formation[50]. Africa is home to millions of cattle. It is often said, colloquially, in some quarters that some African countries have more cattle than humans. The dungs from these cattle, and from pigs, which are also in abundance, can be put into efficient use as RKN control agents. There is however a need to carry out more study towards enhancing their effectiveness and efficiency.

4.4. Cultural control

Cultural control can be in the form of crop rotation, mix-cropping, rouging,phyto-sanitation amongst others. Crop rotation involves the cultivation of different crops, in succession, on the same piece of land year after year. The main objective is usually to conserve soil nutrient, but some additional benefits, aside from nutrient conservation, are associated with this practice. Weed, pests and disease control are some of these benefits. The non-availability of the preferred host of a particular pathogen, especially the obligate ones, can lead to starvation and death after a given period. Such field may then be used to cultivate species of crop or crops that hitherto would have suffered infection from pathogens associated with it. Crop rotation has been used successfully to manageroot-knot and lesion nematodes in the United States of America. The cultivation of potato, which is susceptible to infestation, is usually followed bysorghum, which is resistant,the following cropping season[51]. A similar study carried out in Nigeria gave a promising result both in the greenhouse and field condition. A significant reduction in RKN population was reported in an okra field, where RKN suppressive crop grew the previous season, as opposed to an increase in the population of the pathogen in a similar field subjected to continuous okra cultivation[52]. Mixed cropping can also be used to manage RKN if the right combinations of crops species are used. The different species, some of which must be resistant/repellent to infestation/RKN, will disrupt feeding and breaks the infestation cycle.

A great percentage of farming activities in the continent is carried out by small scale farmers with a limited land resource. Mixed and intercropping are common features on such lands. There may be a need however, to educate farmers on the right crop combinations in rotation and mixed/intercropping farming system. This is imperative if efficient management of RKN on their fields is to be achieved. The importance of rouging and Phyto-sanitation can also not be overemphasized. All that may be required in the management of RKN infestation in some cases, is a diligent and observant farmer. A farmer who is conversant with what a healthy crop looks like and is close to his crop enough to know when things go wrong. RKN infestation can start from one or a few stands of crops. The prompt intervention of the farmer through rouging and treatment of associated soil may be all that is required to prevent a large-scaledisease outbreak and significant crop damage.

4.5. Resistant varieties

The cultivation of crops that are resistant to RKN has several associated benefits. It is cost-effective, safe, non-toxic and environment-friendly. Such crops have been developed and are currently being cultivated all over the world. Cultivars of groundnut (*Arachis hypogeal)*resistant to *M. renaria* and *M. javanica*have been developed in the United States of America and is being used to manage infestation from RKN in different parts of the country[53]. This has increased the management options available to farmers in the country and has brought about increased productivity of the crop. A similar feat has been achieved in Kenya. Several cultivars of potato that are resistant to *M. incognita*(the most common)*M. hapla* and *M. enterolobii* have been identified. These cultivars thrive with minimal root galling in *M. incognita*infested soil[54]. Species of Coffee, *Coffea arabica*, from Ethiopia that is resistant to *M. paranaensis*, one of the most destructive root-knot pathogens of the crop, have been identified. The number of eggs and J2 nematodes were considerably fewer, so also were the number of nematodes per gram of root[55]. Several varieties/cultivars of crops that are resistant to RKN infestation abound in Africa. While many of such crops are imported, others weredeveloped locally by agricultural research institutes and associated agencies. The biggest challenge, however, is getting these cultivarsacross tofarmers in rural communities and convincing them on the need to accept and adopt such cultivars. A lot of work remains to be done in this area.

4.6. Biological control

Biological control has shown promise in the management of several plant pathogenic organisms[56] includingRKN. Biological control has been usedsuccessfully against *Meloidogyne* spp. have been reported. Bacteria, fungi and actinomycetes are the most commonly used biocontrol agents. The mode of action of some of these microorganisms has been explained, and it is either through the conferment of resistance on host crops, thus preventing them from succumbing to infestation, or the degradation of the signaling compounds to which the nematodes are attached. It may also be through the colonization of root surface, which makes it impossible for the infective J2 juvenile to penetrate, production of toxic compounds that are lethal to the nematode or simply through parasitism[57]. Fungi from the two genera, Trichoderma and Purpureocillium have received immense attention as biocontrol agents against RKN. Endospores from bacteria like *Pasteuria penetrans* and *Bacillus firmus* are already being marketed in some countries as ready to use biocontrol agents against nematodes[58]. A combination of antagonistic fungi, *Aspergillus terreus* and *Acremonium strictum*, in a talc-based formulation, produced 66 - 69% efficiency, in terms of inhibition of galling and population of nematodes in the soil. The two fungi established themselves successfully on the rhizosphere of the tomato plant, preventing infestation by *M. incognita*[59]. The technicalities and specificity associated with the use of bio-nematicides is a great challenge that can militate against its adoption in rural Africa. The case is however quite different in multinational and agro-allied industrial farms in urban area and cities, where agriculture experts and other related professionals can be found. Bio-nematicides use can be adopted is such places, while aggressive awarenessand education are launched in rural areas. The campaign should be complemented with pilot farms where practical demonstrations of bio-nematicide use can be carried out for the farmers to see.

4.7. Chemical control

Synthetic chemicals, as management agents, are some of the most effective against RKN. Safety concerns and environmental issues has however resulted in the prohibition of the use of most of these chemicals. High cost, adulteration and counterfeiting are additional issues that African farmers have to contend with. Despite these problems, however, records of successful containment of RKN with the use of synthetic chemicals abound in literature. Dimethoate, at o.5%, suppressed *M. incognita* in tomato, after the roots of young seedling were dipped in it for 6 hrs.[60].Cadusafos toxin (Rugby) at 8 mmp brought about a significant reduction in the population of *M. javanica* in Olive plant[61]. Chemical nematicides are of different types and formulations. They are divided into three major groups, namely; carbamates, fumigants and organophosphates. Aldicarb, Carbofuran and oxamyl are three examples of carbamates, whileFenemiphos,Thionazin and Ebufos are Organophosphates. Chloropicrin, Methyl bromide and Methyl isothiocyanate are fumigants. These names are based on the active components. The trade name varies and is determined by the manufacturers. The developed world is frantically trying to phase out the use of harmful chemical nematicide, the story should not be different in Africa. These chemicals are to be used only when it is extremely necessary, even at that, it should be sparingly and with great caution.

4.8. Integrated management

The emphasis in modern phytopathology is on an integrated approach, as opposed to a sole option, in the managementofplant diseases. Integrated management uses multiple approaches to plant disease management for optimal control of plant pathogens. The aim is to achieve the best result without impacting negatively on the environment. This approach has a better chance of success because it is holistic, taking into account the various factors of disease development, pathogen, host and environment.Examples of successful use of integrated management of RKN has been reported. Maximum rice grain yield was obtained in afield treated with 21 days solarization and application of Carbofuran at 1 kg a.i/ha in a study to manage *M. graminicola* of rice in India[62]. Integrated evaluation of rapeseed cake and botanical nematicide, Bionem, significantly reduced egg hatching and juvenile motility of *M. incognita* of tomato in vitro in Ethiopia[63]. There is no limit to the possible combinations of management options as long as they are compatible and practicable. An integrated approach involving solarization, plants extracts, soil amendment and cultural control will suit most countries in Africa perfectly.

V. Conclusion

There is no denying the fact that RKN are a major threat to crop production and food security in Africa. The low level of awareness about these worms and their activities among the majority of farmers in rural communities is not only pushing the problem to an epidemic proportion but also hampering effective management approach. There is a need for all hands to be on deck to reduce the incidence and severity of infestation to the barest minimum. A lot of work needs to be done on education and training of farmers becausethey are key in the successful implementation of any management strategy. Agricultural research institute across the continent need to focus more on research aimed at stemming the tide of infestation. The government can do more in terms of funding and creating an enabling environment. Donor agencies and non-governmental organizations can also fund or sponsor researches in the field of crop nematology, with particular emphasis on RKN. It is hoped that cooperation and collaboration among the different stakeholders in the value chain of crop production in Africa will bring about a drastic reduction in the menace of RKN.

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