National University of Agriculture
Sciences and Technologies for Sustainable Agriculture (STSA)
ISSN: 1659-5726 (Online) 1659-634X (Print) https://www.stsa.una.bj/index.php/st

VOLUME 4 N° 2 (ORIGINAL ARTICLE)

Management of root-knot nematodes (Meloidogyne spp.) in vegetable production systems in Africa: A comprehensive review and perspectives

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Abstract

Vegetable production is vital for food security in Africa due to its nutritional richness, health benefits, and role in employment generation. Nevertheless, intensive production conditions, such as monoculture and the impacts of climate change, have strongly facilitated the establishment of numerous pathogens and diseases that limit crop yields. Among the various biotic pathogens, root-knot nematodes (RKNs, *Meloidogyne* spp.) are considered one of the most severe biotic pathogens in Africa because of their yield losses. The subterranean lifestyle of RKNs allows their proliferation across multiple crops over several years and facilitates their spread through farming practices, making their management challenging. Therefore, a systematic investigation of affected crops, nematode-induced yield losses, and available sustainable management options is necessary. A thorough literature search was conducted using databases such as Google Scholar, Scopus, and CABI, following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, to comprehensively analyze available data on RKNs and provide synthesized information on their occurrence in Africa, biology and life cycle, host plants, factors promoting their spread, yield losses, and control strategies. These insights are intended to support farmers, researchers, and policymakers in increasing vegetable production in a sustainable way in Africa, thereby contributing to food security. This review highlights the control potential and limitations of the main RKN management methods in Africa and proposes future research directions, particularly, integrated pest management approaches that emphasize biological and cultural control methods.

Keywords: *Meloidogyne* spp., Food security, Pest management, Plant-parasitic nematodes, Africa

Résumé

La production maraîchère est essentielle pour la sécurité alimentaire en Afrique en raison de la richesse nutritionnelle des produits maraîchers, de leurs bienfaits pour la santé et du rôle du maraîchage dans la création d'emplois. Toutefois, les conditions de production intensive, telles que la monoculture et les effets du changement climatique, ont fortement favorisé l'installation de nombreux agents pathogènes et maladies qui limitent les rendements des cultures. Parmi les différents agents pathogènes, les nématodes à galles (*Meloidogyne* spp.) sont considérés comme l'un des pathogènes biotiques les plus redoutables en Afrique en raison des pertes de rendement qu'ils occasionnent. Leur mode de vie souterrain leur permet de se multiplier sur plusieurs cultures pendant de nombreuses années et facilite leur dissémination à travers les pratiques agricoles, rendant ainsi leur gestion particulièrement difficile. Par conséquent, une étude systématique de leur gamme d'hôtes, des dommages potentiels qu'ils causent et des stratégies de gestion durable est nécessaire. Une recherche bibliographique approfondie a été menée à l'aide de bases de données telles que Google Scholar, Scopus et CABI en suivant le protocole PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis), afin d'analyser de manière exhaustive les données disponibles sur les nématodes à galles et de fournir une synthèse des informations relatives à leur occurrence en Afrique, leur biologie et leur cycle de vie, leurs plantes hôtes, les facteurs favorisant leur dissémination, les pertes de rendement qu'ils occasionnent et les stratégies de lutte. Ces éléments visent à soutenir les producteurs, les chercheurs et les décideurs politiques dans l'augmentation durable de la production maraîchère en Afrique, contribuant ainsi à la sécurité alimentaire. Cette revue met en évidence le potentiel de contrôle et les limites des principales méthodes de gestion des nématodes à galles en Afrique et propose des orientations futures de recherche, notamment le développement d'approches de lutte intégrée mettant l'accent sur les méthodes de lutte biologique et culturale.

Mots-clés : *Meloidogyne* spp., Nématodes parasites des plantes, Gestion des ravageurs, Sécurité alimentaire, Afrique

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1- Introduction

Vegetable farming is a major component of agriculture worldwide and is particularly important in Africa because of its nutritional and socioeconomic benefits (Okolle *et al.*, 2016). Rapid urbanization, malnutrition among poor households, and rising food prices have driven its expansion in this region (Mintesnot, 2016). Unlike cereals and legumes, vegetables are cultivated year-round across diverse agro-climatic zones (Burnod *et al.*, 2024). A wide variety of crops, both traditional and exotic, are grown, including *Amaranthus* spp., *Capsicum* spp., *Allium cepa*, *Solanum lycopersicum*, *Daucus carota*, *Allium sativum*, *Brassica oleracea* var. *capitata*, *Pisum sativum*, *Abelmoschus* spp., *Asparagus officinalis*, *Brassica oleracea* var. *italica*, *Apium graveolens* L., *Solanum melongena*, and *Cucumis sativus* (Hunde, 2017; FAO, 2025). These crops are rich in vitamins, minerals, and macronutrients, thereby improving diets and reducing the risks of chronic diseases, such as cancer, diabetes, and cardiovascular disorders (Hunde, 2017). Their high fiber content enhances digestion and blood-glucose regulation, while their hydrating properties are valuable in African regions with limited access to clean water (Okuthe, 2024). Beyond health, vegetable farming supports socioeconomic development by generating household income and creating jobs, particularly for women and youth. Notably, it provides about twice as many jobs per hectare as cereal and legume crops (Mintesnot, 2016; Burnod *et al.*, 2024). Overall, vegetable production is crucial for food security and improved nutrition in African urban areas (Burnod *et al.*, 2024).

Despite their potential, vegetable yields in Africa remain well below expectations (Nordey *et al.*, 2020), even as production has increased recently (Figure 2). Between 2003 and 2023, production grew from 5.04 to 9.23 million tons (83.10%), mainly reflecting the nutritional importance of these crops. Eastern Africa consistently led in production, yet yields dropped by 4.63% over the same period, from 8,791.9 to 8,384.8 kg/ha (Figure 3). East Africa recorded a 34.51% increase in yield, whereas West Africa experienced an 11.58% decline (Table 1). Cultivated areas expanded from 5.73 to 10.10 million ha, with West Africa showing the largest increase (135.47%). At the continental level, despite a 92% increase in area and an 83.10% increase in production, yields decreased by 4.63%. These low yields, especially in West Africa, result from abiotic constraints such as poor soil fertility, drought, irregular water availability, and climate-related heat stress, as well as biotic factors including insect pests, diseases, nematodes, and weeds (Nordey *et al.*, 2017; Ochilo *et al.*, 2019). These biotic agents cause major yield losses and remain a serious threat to vegetable availability (Shai *et al.*, 2024).

Plant-parasitic nematodes (PPNs) are recognized as economically important pest groups affecting vegetable production globally, particularly in Africa (Anushruti *et al.*, 2024). Within PPNs, root-knot nematodes (*Meloidogyne* spp., RKNs) are widely identified as the most destructive and challenging group to manage in tropical regions, especially across the African continent (Talwana *et al.*, 2016). RKNs affect various crops, including vegetables, cereals, tubers, and fruit trees (Belmouden *et al.*, 2025). Their impact is particularly severe in intensive vegetable production systems in Africa, where high temperatures and susceptible crop monoculture favor their proliferation (Chitambo *et al.*, 2019). The key vegetable hosts include tomato, eggplant, pepper, potato, cucumber, lettuce, and carrot (Djian-Caporalino *et al.*, 2009). The parasitism by *Meloidogyne* species on various vegetable crops leads to delayed crop maturity, reduced yields, and reduced quality of crop produce (Dutta *et al.*, 2019; Oso, 2020). Beyond yield losses, RKNs also cause significant socio-economic impacts in African vegetable production systems, including escalating production costs, substantial income losses to farmers, and abandonment of community gardens (Oso, 2020).

To cope with these constraints, farmers often resort to land expansion or the excessive use of nematicides, practices that have serious environmental and health consequences. Such consequences have led to the progressive banning of various nematicides, including methyl bromide, in many countries (Dutta *et al.*, 2019). Moreover, management costs represent a significant economic burden for smallholder farmers (Bernard *et al.*, 2017). Given these challenges, the development of sustainable alternative strategies has become essential. This review focuses on alternative options for managing RKNs, with particular attention to accessible approaches in the African context. These alternative methods include crop rotation, organic amendments, biological control, resistant cultivars, and plant extracts. This review examines the damage caused by RKNs in Africa and their interactions with vegetable crops. The current control methods and their limitations are explored and future perspectives for the sustainable management of RKNs are proposed.

2. *Methodology*

A systematic approach was employed to select articles for analysis in this review. The study followed the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as described by Page *et al.* (2021). This protocol ensures a transparent and reproducible filtering of the literature. It is composed of four main processes, namely identification, screening, eligibility, and inclusion (Aikpon and Ganglo, 2024).

2.1. Identification

The main step is the identification process, which identifies the appropriate keywords for the search process. Two main keywords were applied: Vegetable production and root-knot nematode. To retrieve more relevant articles, the two main keywords were enriched (Shaffril *et al.*, 2021). Therefore, several synonyms, related terms, and variations of the main keywords were sought. Accordingly, a combination of the following keywords and phrases were used for the field Title-Abstract-Keywords: ("root-knot nematode*" OR "root knot nematode*" OR "RKN" OR "*Meloidogyne* spp." OR "*Meloidogyne incognita*" OR "*Meloidogyne javanica*" OR "*Meloidogyne enterolobii*") AND ("management" OR "control" OR sanitation OR monitoring OR surveillance OR "cultural practices" OR "crop rotation" OR "trap crops" OR "cover crops" OR "chemical control" OR "nematicides" OR "biological control" OR "biocontrol" OR "organic amendments" OR "green manure" OR "resistant cultivars" OR "biofumigation" OR "nematicidal plants" OR IPM) AND (

vegetable* OR "vegetable crops" OR tomato OR onion OR pepper OR chili OR okra OR "leafy vegetables" OR "garden crops"). The search process involved three databases: Scopus, CABI, and Google Scholar, taking into account articles, books, institutional reports, and academic theses. The search string was developed based on several essential functions, including field codes, phrase searching, Boolean operators, truncation, and wildcards. In contrast, manual searching (until page 10) based on the handpicking technique was applied in Google Scholar (Shaffril *et al.*, 2024). In this process, 8831 results were preliminarily found in the three databases for the screening process.

2.2. Screening

In this step, screening criteria were set to screen the selected documents. First, it was crucial to ensure that the context of the selected documents was that of African countries and that the crops concerned were vegetable crops. The following criterion refers to timeline publication, in which publications between 2000 and 2025 were chosen for this study. We filtered the information by document type, considering original papers, books, institutional reports, and academic theses in English and French. In addition, duplicate documents across the three databases were eliminated. At the end of this screening process, 468 documents were retained for the following inclusion step.

2.3. Eligibility

Eligibility is the third process performed in this study, whereby the relevancy of each selected article was manually screened by reading the title, abstract, and, if required, the content (Shaffril *et al.*, 2024). At the end of this process, 112 articles were excluded because they focused on non-vegetable crops and did not sufficiently address root-knot nematode (RKN) management strategies in Africa. Non-English and non-French publications and records with no accessible full text were also excluded. Finally, 342 articles were retained for the next step (inclusion).

2.4. Inclusion

The selected documents were appraised for their inclusion. The documents that evaluate, describe, or discuss management methods for root-knot nematodes in vegetable production systems, their economic impacts, and the associated yield losses were included in this study. Studies conducted in African countries that include relevant results on the management of root-knot nematodes were also included. Furthermore, for publications addressing the biology of root-knot nematodes, there was no geographical delimitation. In addition, documents available in English and French and published between 2000 and 2025 were included.

2.5. Data extraction process

The data extracted from the included studies were synthesized and critically appraised. Data retrieved from these studies included data on general information of the documents, including the name of the author(s), year of publication, country of intervention; and study characteristics (Kondo *et al.*, 2025). Outcome results showing the yield losses in vegetable production systems in Africa associated with RKNs and the efficiency of management methods were also retrieved.

Occurrence data of *Meloidogyne* spp. were derived from databases of the Center for Agriculture and Bioscience International (CABI, https://www.cabi.org/). Data on primary vegetable production, yield, and harvested areas from 2003 to 2023 were collected from the FAO statistical database (FAOSTAT) Africa level. The evolution of the increase rate of vegetable crop production from 2003 to 2023 across African regions was determined following the methodology of Epule *et al.* (2022), by calculating the relative change (%):

$$\text{Relative change } (\%) = ((\text{Final Yield} - \text{Initial Yield})/\text{Initial Yield}) \times 100$$

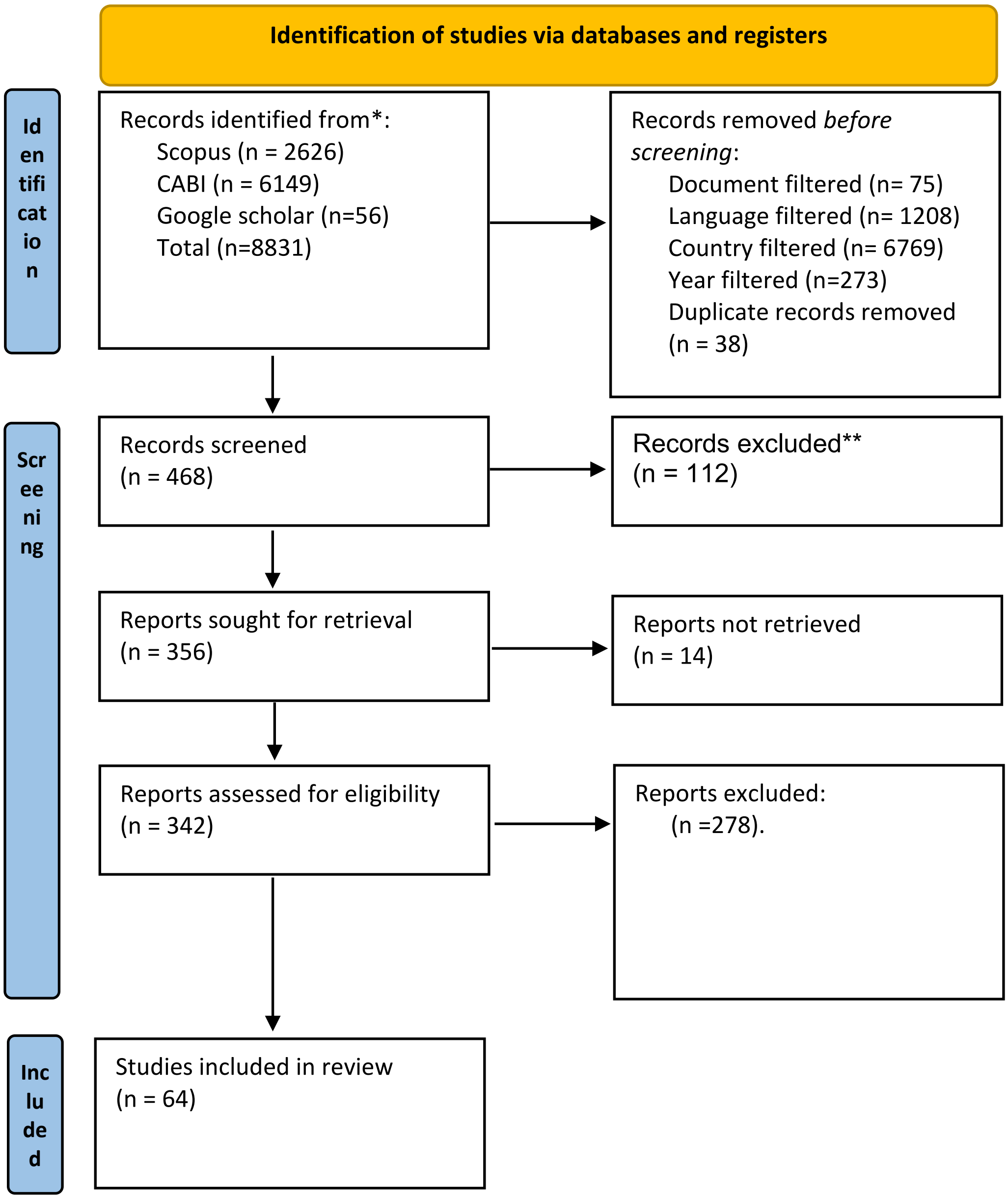

Figure 1. Preferred Reporting Items for Systematic Reviews guidelines to assess the methods of root-knot nematodes management in vegetable production systems in Africa.
n : the number of articles.

3. Vegetable crop production in Africa and root-knot nematodes (Meloidogyne spp.)

3.1. Economic importance of vegetable crops in Africa

Vegetables are a good source of micronutrients in the diet (James and Zikankuba, 2017). In 2023, more than 92 million tons of vegetables were produced in Africa, with a production increase of more than 83.10%% in the last 20 years (Table 1) (FAOSTAT, 2025). The area with the highest vegetable production is Northern Africa (over 36 million tons) (Figure 2), notably in Egypt, Algeria, and Morocco, while Nigeria is the largest producer among sub-Saharan African countries (FAOSTAT, 2025). The cultivation of vegetables is also essential from a socio-economical point of view since it represents a significant source of income for rural producers in several African countries (Mulugeta *et al.*, 2020; Burnod *et al.*, 2024), and therefore improves access to food (Joosten *et al.*, 2015). They also typically provide more employment per hectare than cereals (Schreinemachers *et al.*, 2018). In Niger, vegetable production is considerably more profitable than rice, with per-hectare profits 3.3 times higher and labor-day income approximately doubled (Joosten *et al.*, 2015). In addition, vegetables are an important component of a healthy diet, and their consumption can help prevent a wide range of diseases mainly because of their mineral and vitamin

content (James and Zikankuba, 2017; Hunde, 2017). They are good sources of vitamin C, folate, β-carotene (pro-
vitamin A), potassium, antioxidants, fibers, carotenoids (lycopene), and ascorbic acid (James and Zikankuba, 2017). Potassium in vegetables helps to maintain healthy blood pressure, their dietary fiber content reduces blood cholesterol levels and may lower the risk of heart disease, folate (folic acid) reduces the risks of birth defects, and vitamin A keeps eyes and skin healthy, while vitamin C not only keeps teeth and gums healthy but also aids in iron absorption (Schreinemachers *et al.*, 2018). However, vegetable yields in Africa are still far below their estimated potential (Figure 3), due to some abiotic stresses (drought, floods, and low soil fertility) and biotic stresses (insect pests, microbial plant pathogens, and weeds) (Nordey *et al.*, 2017). RKNs are considered among the major biotic constraints in vegetable production, and they can cause yield losses ranging from 30% to 100% (Faye, 2016).

Table ***Erreur ! Il n'y a pas de texte répondant à ce style dans ce document.*** *: Evolution of the increase rate of vegetable crop production from 2003 to 2023 by region of Africa.*

	Relative Change (%)		
Region			
	Production	Yield	Harvest Area
Eastern Africa	143.64	34.51	81.12
Northern Africa	52.14	23.96	22.73
Southern Africa	20.39	1.43	18.69
Western Africa	108.20	-11.58	135.47
Middle Africa	126.95	24.42	82.40
Africa	83.10	-4.63	92.00

Source : FAOSTAT (2025) and authors' calculations.

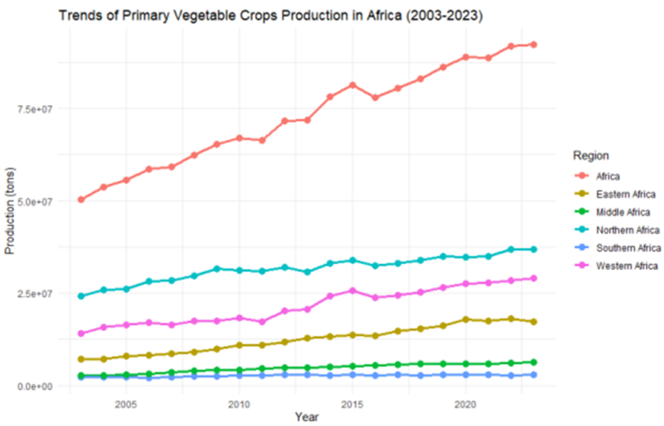

Figure 2: Evolution of vegetable crop production in Africa from 2003 to 2023 by region (source: FAOSTAT (2025) and authors' visualization).

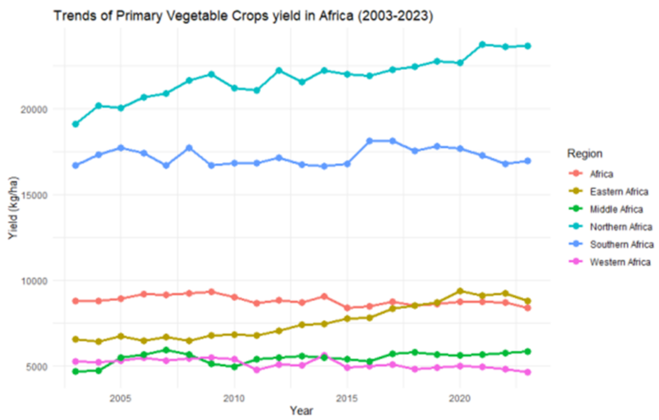

Figure 3: Evolution of vegetable crop yields in Africa from 2003 to 2023 by region (source: FAOSTAT (2025) and authors' visualization).

3.2. Root knot nematodes (Meloidogyne spp.) of vegetable crops

3.2.1. Taxonomy, host range, and occurrence of Meloidogyne spp. in Africa

3.2.1.1. Taxonomy

RKN are eukaryotic organisms belonging to the kingdom Metazoa, phylum Nematoda, class Secernentea, order Tylenchida, family Heteroderidae, and genus *Meloidogyne* (Wendimu, 2021). The *Meloidogyne* genus comprises approximately 100 species, but four RKN species are of major economic importance globally because of their widespread distribution: *M. arenaria*, *M. incognita*, *M. javanica*, and *M. hapla* (da Silva *et al.*, 2019). Recently, a new species, *M. enterolobii*, has emerged as a significant RKN species with increasing global reports (da Silva *et al.*, 2019). Initially identified in China, this species has now expanded across several African countries and South America (da Silva *et al.*, 2019).

3.2.1.2. Host range and occurrence of major Meloidogyne species in Africa

The distribution of the four major *Meloidogyne* species across Africa, as well as their host plants, is presented in Table 2.

Table 2: Host range and occurrence of Meloidogyne spp in Africa

Meloidogyne spp.	Country/Region	Main crop(s) affected	References
M. arenaria	Algeria, Cote d'Ivoire, Egypt, Gambia, Ghana, Liberia, Libya, Madagascar, Malawi, Mauritius, Morocco, Mozambique, Nigeria, Sao Tomé and Principe, Senegal, South Africa, Sudan, Tanzania, Uganda, Zimbabwe, Benin	Potato, sweet potato, tomato, okra, cassava, groundnut, wheat, oats, watermelon, bell pepper, chili, arabica coffee, cucumber, marrow, carrot, soyabean, cotton, lucerne, banana, tobacco, rice, peach, guava, maize, date palm, peach, tea, lettuce, aubergine, soybean, pineapple, pyrethrum, papaya, cowpea, and velvet bean	Onkendi *et al.*, (2014) ; Coffi et *al.*, (2025a) Makhubu, (2021) and CABI (2025)
M. enterolobii	Malawi, Senegal, South Africa, Cote d'Ivoire, Burkina Faso, Benin, Democratic Republic of Congo	Potato, guava, and tomato	Onkendi *et al.* (2014); CABI, (2025) ; Coffi et *al.* (2025a)
M. hapla	Algeria, Cote d'Ivoire, Egypt, Kenya, Libya, Malawi, Morocco, Nigeria, South Africa, Tanzania, Uganda, Zimbabwe	Coffee, carrot, banana, tomato, melon, potato, lettuce, Chinese gooseberry, groundnut, sugarbeet, chicory, strawberry, soyabean, tobacco, and date palm	Onkendi *et al.* (2014) ; Makhubu, (2021); CABI (2025)
M. incognita	Algeria, Angola, Botswana, Burkina Faso, Cameroon, Congo, Democratic Republic of Congo, Cote d'Ivoire, Egypt, Ethiopia, Gambia, Ghana, Guinea, Kenya, Liberia, Libya, Madagascar, Malawi, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Benin, Reunion, Sudan, Tanzania, Tunisia,	Potato, tomato, cassava, sugarcane, banana, sweet potato, date, tobacco, broad bean, celery, upland rice, aubergine, chinese cabbage, cassava, papaya, coffee, kenaf, lettuce, lucerne, rice, pepper, grapevine, soybean, maize, date palm, coconut, cowpea, cauliflower, okra, eggplant, cabbage, onion, watermelon,	Onkendi *et al.* (2014); Makhubu (2021); CABI (2025)
M. incognita	Uganda, Zambia, Zimbabwe, Senegal, Seychelles, Somalia, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia	African spinach, mango, citrus, banana, guava and numerous crops	Onkendi *et al.* (2014); Makhubu (2021); CABI (2025)
M. javanica	Aldabra, Algeria, Angola, Burundi, Comoros, Democratic Republic of Congo, Cote d'Ivoire, Egypt, Eritrea, Gabon, Gambia, Ghana, Kenya, Liberia, Libya, Madagascar, Malawi, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Nigeria, Benin, Reunion, Rwanda, Senegal, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe	Potato, tomato, sugarcane, banana, yam, sweet potato, date, tobacco, broad bean, celery, tomato, rice, aubergine, chinese cabbage, cassava, bell pepper, tobacco, date palm, buchu (*Agathosma betulina*), and numerous other crops	Onkendi *et al.* (2014); Makhubu (2021); CABI, (2025)

3.2.2. Morphology, life cycle, and mode of infestation of Meloidogyne spp.

RKN act as obligate biotrophic parasites, completing their life cycle within the roots of a living host (Philbrick *et al.*, 2020). They are sedentary endoparasites that feed entirely within the root tissues and reach adulthood (Philbrick *et al.*, 2020). Their life cycle comprises an exophytic phase (eggs and infective second-stage juvenile J2) and an endophytic phase (sedentary J3, J4, and adults) (Mejias, 2020). The developmental stages exhibit distinctive morphological characteristics that allow species differentiation, including the perineal pattern of females, stylet and excretory pore, cephalic framework in males, and head and tail features of J2 (Philbrick *et al.*, 2020). Adult females are generally globose or pyriform, white in color, with a prominent neck and a well-developed stylet (Philbrick *et al.*, 2020; Wendimu, 2021). Their morphometrics vary among species, but overall, they range from 600 to 1,300 µm in length and 300 to 600 µm in width, with a stylet measuring 10–17 µm (Mirzaev *et al.*, 2024). Males are vermiform, translucent, and have a longer stylet than females (averaging 15–25 µm). Their body generally reaches 1,000–1,700 µm in length (Philbrick *et al.*, 2020). Second-stage juveniles (J2s) are vermiform, whitish, and transparent, with a rounded head, a robust stylet, and a slender tail ending with a hyaline terminus. Their body length ranges from 300 to 600 µm, the tail from 30 to 70 µm, and the stylet from 9 to 14 µm (Philbrick *et al.*, 2020; Mirzaev *et al.*, 2024). Although these parameters vary between species, they are essential for the accurate identification of the species.

The life cycle of *Meloidogyne* spp. is similar across species. Females lay their eggs in a gelatinous matrix extruded into the soil or at the root surface (Wendimu, 2021). Following embryogenesis, J2s hatch and invade the roots, penetrating the epidermal tissues before migrating toward the vascular cylinder, where they establish giant cells that function as permanent feeding sites and are responsible for gall formation. Penetration results from both the mechanical action of the stylet and the secretion of cellulolytic and pectolytic enzymes (Philbrick *et al.*, 2020). J2s undergo three molts, progressing through stages J3 and J4 to become adult males or females, but only females reproduce (Philbrick *et al.*, 2020). The J3 and J4 stages as well as the males are non-feeding. Males typically develop under unfavorable conditions (e.g., extreme soil temperatures or insufficient soil moisture) and migrate out of the root system (Philbrick *et al.*, 2020). Females remain sedentary, continue feeding, enlarge, and acquire a pear-shaped morphology (Philbrick *et al.*, 2020). They oviposit bean-shaped eggs from which new J2s emerge to infest fresh roots, thereby perpetuating the cycle. The full cycle lasts 30–35 days under favorable conditions, with each female producing up to 600 eggs (da Silva *et al.*, 2019; Philbrick *et al.*, 2020).

Reproductive modes vary among species and include amphimixis, meiotic parthenogenesis, and mitotic parthenogenesis (Chitwood and Perry, 2010). For example, *M. hapla* can reproduce sexually or via meiotic parthenogenesis (Castagnone-Sereno and Danchin, 2014), whereas *M. enterolobii* reproduces exclusively via obligate mitotic parthenogenesis (Castagnone-Sereno *et al.*, 2013). *M. incognita*, *M. javanica*, and *M. arenaria* primarily reproduce via parthenogenesis. Conversely, some narrow-host-range species, such as *M. megatyla* and *M. microtyla*, reproduce exclusively by amphimixis (Nilusmas, 2020).

3.2.3. Factors influencing nematode proliferation

RKNs are among the most destructive sedentary plant-parasitic nematodes, and their survival and proliferation are strongly influenced by soil and climatic factors. Light sandy soils with low clay content favor their mobility, root colonization, and reproduction, leading to severe galling and egg mass production compared to heavier soils (Wendimu, 2021). Temperature is a critical regulator of nematode biology that affects hatching, development, and reproduction. Optimal egg hatching temperature varies by species: *M. chitwoodi* and *M. fallax* hatch best around 20 °C, whereas *M. incognita*, *M. javanica*, and *M. hapla* hatch best near 30 °C (Tsai *et al.*, 2010; Khan *et al.*, 2014). The development of *M. incognita*, *M. arenaria*, and *M. javanica* is halted at 12 °C–15 °C but accelerated between 25 °C and 30 °C, while *M. hapla* favors cooler conditions near 20 °C (Dávila-Negrón and Dickson, 2013 Velloso *et al.*, 2022). Excessive heat (≈40 °C) inhibits female maturation in most species (Tsai *et al.*, 2010). Soil moisture between 10–30% is necessary for juvenile survival, while 40 - 60% enhances penetration, hatching, and crop damage; conversely, waterlogged soils restrict survival due to oxygen depletion (El-Saadony *et al.*, 2021). Agricultural practices also influence RKN populations: deep tillage may increase egg density, mulching can create favorable microclimates, and inadequate fallowing often intensifies infestations (El-Saadony *et al.*, 2021).

3.2.4. Symptoms and damage

In tropical and subtropical regions, RKNs are soil-borne pests that severely damage diverse crops, especially vegetables (Choudhary *et al.*, 2024). Damage arises from the invasion of J2s, whose penetration and feeding induce multinucleate giant cells and root galls (Petrikovszki *et al.*, 2023). These galls, the hallmark of infestation, impair water and nutrient uptake by disrupting vascular tissues, thereby slowing growth (Choudhary *et al.*, 2024). Other symptoms include chlorosis, leaf yellowing, wilting, and stunting (Ali *et al.*, 2023). However, these effects are not specific to nematode attack, as similar effects may stem from water stress, nutrient deficiency, or other pathogens (Ali *et al.*, 2023). J2 penetration also creates entry points for fungi and bacteria, whose colonization exacerbates root damage and disease severity (Ali *et al.*, 2023; Coffi *et al.*, 2025a). Infestation further causes irregular distribution of plants in cultivated plots.

3.2.5. Yield loss and fruit quality deterioration

RKNs are soilborne pathogens that cause substantial reductions in both yield and quality of vegetable crops worldwide, including across Africa. Average yield losses of approximately 10% are commonly reported in vegetable production (Anushruti *et al.*, 2024). However, the magnitude of these losses is highly variable and depends on several factors, including the nematode species involved, their population density, host plant species, and local agroecological conditions (Nilusmas, 2020). For example, Sikora *et al.* (2018) reported yield reductions exceeding 30% in highly susceptible crops, such as eggplant, tomato, and melon. In tropical and subtropical regions under severe infestation, yield losses may reach up to 80% (Sikora *et al.*, 2018). More recently, Elkhiat *et al.* (2025) reported losses in susceptible tomato cultivars over 70%. An estimated loss of nearly 91% has been reported (Faye, 2016); while 30% and 45% have been observed in melon and carrot, respectively (Jones *et al.*, 2017; Chitambo *et al.*, 2019). Under protected cultivation systems in the Mediterranean basin, losses of up to 37%, 60%, and 80% have been reported for watermelon, cucumber, and pepper, respectively, due to RKNs infestations (Nnamdi *et al.*, 2022; Talavera-Rubia *et al.*, 2022). Global crop losses due to RKNs are estimated at approximately 60%, with losses in African vegetable systems ranging from 30% to 100% (Faye, 2016). For instance, in Ghana, RKNs account for up to 33% of seasonal vegetable losses, of which 73% - 100% occur in tomato cultivation (Okorley *et al.*, 2018).

RKNs also compromise the product quality by disrupting the plant physiological processes and inducing the morphological changes in fruit structure (Hajihassani *et al.*, 2019). Nematode parasitism negatively affects fruit size, firmness, and biochemical attributes, such as soluble solid content and specific metabolite concentrations (El-Eslamboly *et al.*, 2019).

3.2.6. Economic loss and implications for food security

RKNs cause substantial economic losses due to their high reproductive potential, extensive host range (> 5,500 plant species), and wide geographic distribution (Choudhary *et al.*, 2024). According to the American Society of Phytopathology (APS), it is estimated that economic losses in the agricultural sector due to nematodes represent 14% of the worldwide crop yield losses, which is almost 125 billion dollars annually (Mesa-Valle *et al.*, 2020). Data are scarce in Africa (Onkendi *et al.*, 2014; Coyne *et al.*, 2018), but yield reductions of 30%–100% reported highlight the serious threat to vegetable production (Faye, 2016).

With the global population projected to reach 9–10 billion by 2050, including over 2 billion in Africa (Afzal and Mukhtar, 2024), food production is required to increase by more than 50% (Talwana *et al.*, 2016). However, RKNs represent a major constraint to achieving this goal, thereby posing a significant threat to global food security. In 2020, UNICEF reported more than 15 million cases of acute malnutrition in West and Central Africa (Simon *et al.*, 2020). In this context, where vegetable production and consumption are key strategies to improve nutrition and food security, RKNs limit the availability of nutrient-rich foods and jeopardize dietary quality for African populations that depend on agriculture for their livelihoods (Chitambo *et al.*, 2019).

3.2.7. Management strategies for root-knot nematodes in Africa

3.2.7.1. Conventional approaches

- *Use of chemical nematicides*

Historically, chemical control has been the predominant strategy for the suppression of RKNs (Khder *et al.*, 2025). Conventional agriculture has relied heavily on the widespread use of synthetic pesticides to combat pests, particularly since the first Green Revolution following World War II, with the aim of increasing yields and doubling global food production (Boulestreau, 2021). In Africa, nematicides are among the earliest and most effective options used to manage RKNs (Onkendi *et al.*, 2014; Cuvaca *et al.*, 2025). In Eastern and Southern Africa (ESA), although the use of nematicides has been associated with large-scale and commercial farms producing commodities such as banana, their use is increasingly reported in vegetable production systems, particularly in tomato cultivation (Cuvaca *et al.*, 2025). Recent reports indicate that up to 20% of vegetable producers in the ESA region have adopted nematicides for RKNs management, despite the high costs associated with these inputs (Cuvaca *et al.*, 2025). The nematicides applied to the soil prior to planting are classified either as fumigants or non-fumigants, based on their mobility within the soil profile (Makhubu *et al.*, 2021; Cuvaca *et al.*, 2025).

Fumigants, such as chloropicrin, metam sodium, dimethyl disulfide (DMDS), iodomethane, ethylene dibromide (EDB), 1,2-dibromo-3-chloropropane (DBCP), 1,3-dichloropropene (1,3-D), and methyl bromide, are gaseous or low-molecular-weight compounds with broad-spectrum biocidal activity that target nematodes, soil fungi, and bacteria (Desaeger *et al.*, 2020). In African countries, registered fumigants include 1,3-D, EDB, 1,3-D combined with chloropicrin, metam potassium, metam sodium, and methyl bromide/chloropicrin mixtures (Onkendi *et al.*, 2014; Jones, 2017). Non-fumigants are formulated as granules or liquids and are typically applied to the soil in furrows, bands, or by broadcast application, and they typically exhibit reduced persistence of toxic molecules in the environment compared with fumigants (Cuvaca *et al.*, 2025). Non-fumigants available include carbamates (aldicarb, aldoxycarb, oxamyl, carbofuran, and cloethocarb), organophosphates (ethoprophos, cadusafos, terbufos, imicyafos, fosthiazate, thionazin, fenamiphos, fensulfothion, tiazofos, and ebufos), and macrocyclic lactones (avermectins and milbemycins produced by *Streptomyces* spp.), which generally show narrower specificity but are effective at lower concentrations (Onkendi *et al.*, 2014; Oka, 2020).

Several studies in Africa have demonstrated the effectiveness of chemical nematicides. For example, in Egypt under controlled conditions, the application of ethoprophos, oxamyl, and abamectin reduced *M. incognita* population densities and the number of galls on tomato roots, resulting in improved tomato plant growth (Khalil and Alqadasi, 2019). In another pot experiment conducted in Egypt, Saad *et al.* (2017) reported that egg-masses, eggs per egg-mass, and J2s were significantly reduced on tomatoes treated with fenamiphos, oxamyl, and cadusafos.

Despite their efficacy in rapidly reducing nematode populations and improving yields, nematicides pose numerous problems. Environmental issues include contamination of soil, water, and air, as well as impacts on non-target organisms such as beneficial arthropods, springtails, carabid beetles, and earthworms (Oka, 2020; Makhubu *et al.*, 2021). Human health risks arise from exposure to toxic formulations, particularly emulsifiable concentrates, and from neglecting pre-harvest intervals, leading to residues on fresh produce (Tiwari, 2024). Repeated applications can promote resistance in *Meloidogyne* populations and contribute to high production costs, with a single nematicide development averaging USD 200 million (Oka, 2020).

Despite bans and international regulations, nematicides are still widely used in Africa due to weak national legislation and enforcement (Jirata *et al.*, 2024). They remain among the preferred methods for RKNs control (Radwan *et al.*, 2012). New compounds, including fluopyram, fluensulfone, and fluazaindolizine, are promising (Desaeger *et al.*, 2020). However, nematicides should be used as a last resort and preferably in combination with other preventive, sustainable, and environmentally friendly agronomic or cultural practices listed in the following sections (Cuvaca *et al.*, 2025).

- *Genetic improvement and resistant varieties*

The use of resistant vegetable cultivars or rootstocks is a promising and environmentally friendly strategy for RKNs management. Resistance mechanisms in resistant cultivars are generally categorized as pre- or post-penetration (Ramatsitsi and Ramachela, 2023). Pre-penetration resistance prevents juvenile invasion through root exudates or structural barriers, whereas post-penetration resistance involves the synthesis of secondary metabolites that induce phytoalexin accumulation, nematicidal activity, and hypersensitive responses, thereby inhibiting feeding, J2 development, and reproduction. Post-penetration resistance can occur early (during nematode migration or initial giant cell formation) or late (after giant cell establishment). This strategy gained momentum following the withdrawal of many chemical nematicides. Resistant cultivars have been reported worldwide, e.g., carrot (273, 450, 453, 454) resistant to *M. incognita* race 1 in South Korea; tomato (EC705452, Arka Vardana, NT-3, Pusa Hybrid-2, Sanibel) in India and the USA; chili pepper (Surajmukhi, Mohini, Pusa Jwala) and eggplant (Black Beauty, KS-224) in India (Kumar *et al.*, 2023). In Africa, resistant genotypes include amaranth (Local 33), pepper (cv. Tabasco), and tomato (Rhapsody, MFH 9324, FA 1454, FA 593) in South Africa; tomato Mongal T-11 and Beef Master in Ghana (Jaiteh *et al.*, 2012); tomato F2 and BC1.1 and pepper Carolina Cayenne, Carolina Wonder, Charleston Belle (Kwara *et al.*, 2014; Frimpong *et al.*, 2022); and tomato lines CLN-2366A/B/C resistant to *M. incognita* and *M. javanica* in Ethiopia (Seid *et al.*, 2015).

Nematode-resistant cultivars have the intrinsic ability to be unaffected significantly upon nematode attack, and will greatly contribute to reducing nematode infestations in fields (Okorley *et al.*, 2018). Using resistant cultivars has proven effective to manage RKNs and improve yield in tomato and pepper cultivated in naturally infested nematode soils (Kwara *et al.*, 2014). Resistance to RKN species (*M. incognita*, *M. javanica*, and *M. arenaria*) is conferred by a single dominant Mi gene in commercially cultivated crops (Okorley *et al.*, 2018). Several studies in Africa have demonstrated the effectiveness of resistant cultivars in managing nematodes (Banora and Almaghrabi, 2019; Beyan *et al.*, 2019).

However, the use of resistant cultivars to manage RKNs remains less explored. Additionally, its effectiveness is limited at higher soil temperatures, or by RKN race or species (Regmi and Desaeger, 2020). Overall, the efficacy of resistant cultivars can be enhanced by complementary practices, such as crop rotation, biofumigation, or biological control.

3.2.7.2. Alternative and agroecological approaches

- *Prevention*

Preventing nematode infestations is the first line of defense. The spread of nematodes can be mitigated through the implementation of effective sanitation practices. Sanitation is essential for avoiding primary infections (introduction into a field) and avoiding secondary infections (spreading within the field) (Anushruti *et al.*, 2024; Harrison *et al.*, 2024). Sanitation practices, such as removing plant debris, cleaning farm equipment, and ensuring that transplants and soil are free from nematode contamination can help minimize the introduction of nematodes into clean fields (Devi *et al.*, 2024; Harrison *et al.*, 2024). For instance, in Kenya, farmers implemented field sanitation, such as rouging infected tomato plants, burying/burning infected plants (Birithia and Kuria, 2023). In South Africa, farmers uproot and expose the tobacco residues to sunlight after harvest or burn them in situ (Wendimu, 2021).

- *Monitoring and surveillance:*

Effective monitoring and surveillance are essential for the success of any pest and disease management program (Devi *et al.*, 2024). Monitoring and surveillance consist of a diagnosis based on regular soil sampling and plant inspection to detect nematode populations and assess their potential impact (Devi *et al.*, 2024; Harrison *et al.*, 2024). Sampling should be done at regular intervals, particularly before planting and during the growing season, to identify the nematode species present. The commonly used methods for the identification of RKNs include morphological characterization, biochemical profiling, and molecular diagnostic techniques (Wendimu, 2021). Unfortunately, in Africa, poor infrastructure networks and limited capacities for pest and disease diagnosis remain prevalent (Coyne *et al.*, 2018). Regarding plant inspection, it includes observing plant health, particularly root systems. Symptoms like root galls, stunted growth, wilting, and yellowing leaves may indicate the presence of nematodes, prompting further investigation (Devi *et al.*, 2024). By inspecting roots and plants regularly, farmers can identify potential nematode issues early and take action to manage the problem. Unfortunately, these symptoms are often attributed to unknown causes, nutrient deficiency, and soil sickness (Coyne *et al.*, 2018). To ensure effective monitoring and surveillance of RKNs in Africa, additional efforts from nematologists are needed to train and raise awareness among farmers and extension agents on the preliminary diagnosis of nematodes (through plant inspection).

- *Crop rotation and trap cropping*

Crop rotation is the practice of planting crops from different families sequentially on the same plot of land to combat pests and diseases, among other benefits (Otieno *et al.*, 2023). This practice disrupts the nematode life cycle by depriving them of their preferred host crops. Monoculture of susceptible vegetable crops, such as tomato, on soil infested with RKNs can be highly detrimental, causing severe yield losses in tropical and subtropical regions (Sikora *et al.*, 2018). Consequently, to reduce nematode populations in the soil, rotation of susceptible crops with trap crops or non-host crops is often employed. However, choosing an inappropriate crop for rotation may not only worsen nematode-related problems but also adversely affect other pests and diseases (Sikora *et al.*, 2023). Suitable crops for rotation with host crops such as Solanaceae include barley (*Hordeum vulgare*), oat (*Avena sativa*), cotton (*Gossypium hirsutum*), certain grasses, sorghum, maize, castor bean, *Crotalaria* spp., and various Brassicaceae, notably cabbage, cauliflower, mustard, and Chinese cabbage (Otieno *et al.*, 2023). Rotation among tomato, eggplant, and other solanaceous species should be avoided. The effectiveness of crop rotation depends on the rotation length, crop species involved, and soil type (Ngelenzi-Munywoki *et al.*, 2022; Otieno *et al.*, 2023). The strategy of crop rotation and intercropping has been shown to increase yield and are well regarded by farmers, particularly in countries with low crop productivity (Cuvaca *et al.*, 2025). Previous reports have demonstrated the potential of crop rotation to reduce RKNs population densities in different African countries.

Despite its success, this method is limited when multiple nematode species are present or when implemented over short durations. Accurate identification of target nematode species and their host range is essential before designing a rotation scheme, while maintaining a rotation cycle of at least 4 years to achieve significant reductions in nematode densities (Azlay *et al.*, 2023). Another limitation of crop rotation is its economic unsuitability for specialized, large-scale intensive commercial systems, where it may not be viable for many growers (Sikora *et al.*, 2023). Therefore, although crop rotation contributes to nematode suppression, it is most effective when integrated with complementary management strategies. Its effectiveness can be enhanced by complementary practices, such as the use of trap crops, which are capable of diverting nematodes away from the main crop (Cuvaca *et al.*, 2025). Several trap crops, including radish (*Raphanus sativus*) and mustard (*Brassica juncea*), have been shown to successfully suppress *Meloidogyne* spp. (Cuvaca *et al.*, 2025).

- *Biological control*

Biological control is an eco-friendly approach to managing RKNs, reducing chemical dependency, and promoting beneficial soil organisms (Afzal and Mukhtar, 2024). It uses living organisms to regulate nematode populations (Otieno *et al.*, 2023). Soil bacteria and fungi naturally antagonize nematodes and act as biological control agents (Azlay *et al.*, 2023).

Nematophagous bacteria have shown potential against nematodes, acting through different mechanisms, such as parasitizing nematodes through attachment to the nematode cuticle (i.e., *Pasteuria penetrans*, *P. thornei*, and *P. nishizawae*), producing nematicidal toxins, or inducing plant systemic resistance (i.e., Bacillus *firmus*) (Azlay *et al.*, 2023). Plant growth-promoting rhizobacteria (PGPR), such as *Pseudomonas* and *Bacillus*, act directly via phytohormones or indirectly via secondary metabolites and plant resistance induction (Azlay *et al.*, 2023). In Africa, the use of nematophagous bacteria, alone, or in combination with resistant cultivars, is gaining interest among smallholders, particularly in Kenya, Tanzania, and Uganda (Cuvaca *et al.*, 2025). Several African countries, including Kenya, Tanzania, and South Africa, have also adopted biopesticides, such as *P. penetrans*, in vegetable cultivation (Cuvaca *et al.*, 2025).

Nematophagous fungi also antagonize RKN and are classified by infection strategy: nematode-trapping fungi, egg/female parasites, endoparasites, toxin-producing fungi, or fungi with specialized attack structures (Azlay *et al.*, 2023). Key genera include *Arthrobotrys*, *Monacrosporium*, *Gamsylella gephyropaga*, and *Pochonia chlamydosporia*. Fungi, such as *Trichoderma*, mycorrhizal fungi, and endophytes, can enhance plant resistance and mitigate nematode damage (Affokpon *et al.*, 2018).

Biological control can be considered as an option for managing nematodes. However, its efficacy depends on several factors, including the selection and deployment of appropriate biocontrol agents, environmental conditions, and overall soil health (Afzal and Mukhtar, 2024). The natural variability of nematode populations and their adaptability to new environments can limit the effectiveness of biological control. Consequently, it should be integrated with other management strategies to ensure long-term success.

- *Biofumigation and nematicidal plants*

Biofumigation, initially defined as the suppressive effect of decomposing Brassica tissues, is now more broadly referred to as the biological degradation of plant or animal residues that produce volatile biocidal compounds (Dutta *et al.*, 2019). It represents a nonchemical strategy for managing RKNs. The biocidal effects of Brassicaceae result from isothiocyanates released via glucosinolate hydrolysis catalyzed by myrosinase, as well as sulfur-containing volatile toxins formed during decomposition (Dutta *et al.*, 2019). Biofumigation involves either (i) incorporating chopped aerial parts into moist soil as amendments (green manures or seed meals) or (ii) using poor-host Brassica species as cover/rotation or trap crops to stimulate RKN activity without reproduction (Dutta *et al.*, 2019). The capacity of certain plants to suppress nematodes through the nematicidal activity of secondary metabolites has been demonstrated by numerous investigations in the literature (Youssef and Lashein, 2013; Mashela *et al.*, 2017). Key biofumigant Brassica species include *B. oleracea*, *B. napus*, *B. rapa*, *Raphanus sativus*, *B. campestris*, *B. juncea*, *Sinapis alba*, *B. nigra*, *B. carinata*, and *Eruca sativa* (Dutta *et al.*, 2019). Other plants also exhibit biofumigation potential against RKNs. Sorghum, Sudan grass, *Melia azedarach*, and *Tagetes* spp. have been reported to be effective (Otipa *et al.*, 2009; Muiru *et al.*, 2017). In Africa, species such as *Cassia abbreviata*, *Cissus cactiformis*, *Cucumis africanus*, *Ricinus communis*, *Senna petersiana*, and *Euphorbia ingens* possess nematicidal properties and could serve as biofumigants (Makhubu *et al.*, 2021). Biofumigation can be employed independently or in combination with other treatments such as sanitation, organic amendments, and crop rotation (Feyisa, 2022). Furthermore, biofumigation should be implemented with caution, as it can negatively impact beneficial soil microbial communities through the uncontrolled release of toxic compounds (Dutta *et al.*, 2019).

- *Organic amendments*

Organic amendments are added to soil to improve its physical, chemical, and biological properties (Tefu *et al.*, 2022). They are derived from plant or animal sources, including garden waste, plant residues or extracts, manures, oil cakes, ashes, composts/ or vermicomposts, and biochar. They enhance soil structure, porosity, water-holding capacity, and aggregate stability, thereby supporting higher agricultural productivity (Devi *et al.*, 2020). Additionally, organic amendments help manage plant diseases and soilborne pathogens by reducing their incidence and severity (Rosskopf *et al.*, 2020). Therefore, they represent a promising alternative for nematode management within integrated pest management frameworks (Tefu *et al.*, 2022). Their effects on RKNs operate through multiple mechanisms: (i) release of pre-existing nematicidal compounds, (ii) generation of nematicidal substances such as ammonia and fatty acids during decomposition, (iii) stimulation or introduction of antagonistic microorganisms, (iv) increased plant tolerance and resistance, and (v) alteration of soil conditions unfavorable to nematode activity (Oka, 2010; Bouchtaoui *et al.*, 2024).

3.2.8. Managing the root-knot nematodes in vegetable production : Success stories from Africa

In Africa, plant-parasitic nematodes research has been increasing, with both RKNs attracting the most attention (Cuvaca *et al.*, 2025). RKNs are economically damaging nematodes on a range of crops in African climates (Coyne *et al.*, 2018). The most employed tactic for managing RKNs in Africa is nematicides (Khalil *et al.*, 2019). Furthermore, they have a restricted use in the market because some of them pose threats to human health and other living organisms, as well as environmental hazards including ozone layer depletion, groundwater contamination, and other serious ecological risks (Oka, 2020). In the process of identifying alternative, more environmentally friendly control options for the control of RKNs, several bioassays have been conducted in Africa. The results of these assays are presented in the following paragraph.

3.2.8.1. Crop rotation and root knot nematodes control

Crop rotation is a cultural method and it is among the most common strategies for controlling PPNs in cropping systems in Africa (Cuvaca *et al.*, 2025). Different crop combinations showed the potential to reduce RKNs population densities and were recommended in different African countries. Among them, rotation of tomato with maize under both greenhouse and field conditions reduced the population densities of RKNs and increased tomato yield in Kenya (Luambano-Nyoni *et al.*, 2014). Similarly, *Crotalaria brevidens*, when used in rotation, reduced RKNs population densities by 27.8% in tomato, while improving tomato yield in Kenya (Ngelenzi-Munywoki *et al.*, 2022). In Nairobi, Kimenju *et al.* (2010) observed a reduction in RKN severity, with a score of 3.3 on okra following rotation with sweet maize, compared with 8.6 under continuous okra monoculture. Similarly, *Tagetes patula* and *T. minuta*, when used either in rotation or as cover crops, reduced the population densities and the damage caused by RKNs in tomato (Opita *et al.*, 2009). Crop rotation of okra with guwar (*Cyanopsis tetragonoloba*) and sweet maize (*Zea mays* var. saccharata) reduced mixed populations of *M. incognita* and *M. javanica* by 21 and 44%, respectively, while increasing okra yield by 60 - 92% (Mweke *et al.*, 2008). RKNs populations were also reduced by 85% in tomato crops following three successive growing seasons of *Amaranthus dubius*, *Amaranthus cruentus*, and *Solanum scabrum*, compared with continuous tomato cultivation (Chitambo *et al.*, 2019).

These results show that the effectiveness of crop rotation depends on the rotation crop, the host crop, and the duration of the rotation and its effectiveness can be evaluated based on the suppression of nematode population density, the reduction of the gall index, and an improvement in crop yield.

3.2.8.2. Resistant cultivars and root knot nematodes control

Resistance genes in response to root-knot nematode infection suppress one or more of several critical steps in nematode parasitism and their reproduction rate (Banora and Almaghrabi, 2019). Studies by Kwara *et al.* (2014) have shown that resistant tomato varieties such as Small Fry, Jetsetter and Celebrity, as well as pepper cultivars including Carolina Cayenne, Carolina Wonder, and Charleston Belle, supported low reproduction of *Meloidogyne* spp. (4.5 to 12.3 eggs/5 g compared with 54.6 eggs/5 g for control) and exhibited low root gall rating scores (score 1 out of 5 compared with 4 out of 5 for control) under field conditions in Ghana. Similarly, pepper (*Capistrano frutescence*) cultivar 'Capistrano' exhibited resistance to *M. incognita* race 2, with a reproduction factor below 1, under greenhouse conditions in South Africa (Mashela and Pofu, 2012). In Nigeria, accessions NG/TO/JUN/09/007, NHGB/10/048, NG/AA/SEP/09/040, NHGB/09/057, and NG/SA/DEC/07/0528 were tolerant to *M. incognita* (Odeyemi *et al.*, 2016). In Ghana, the *Solanum* rootstock "Samrudhi F1" was resistant in both pot and field trials and consistently decreased nematode root galling (<1.00) and reproduction ($Rf < 1.00$) (Okorley *et al.*, 2018). In another test, the tomato genotype "Assila" was found to be moderately resistant, significantly reducing the number of root galls and egg-masses per plant compared to the susceptible Marmande genotype (Beyan *et al.*, 2019). Banora and Almaghrabi (2019) also reported tomato genotypes (Jampakt, Malika and Nema Guard) are resistant to RKNs.

These results highlight the need to intensify breeding for resistant genotypes using approaches such as conventional selection, marker-assisted selection, gene editing, or genetic engineering (Afzal and Mukhtar, 2024). The regular screening of newly introduced varieties is also crucial for smallholder farmers reliant on local seed markets (Mashela *et al.*, 2017). However, breeding requires several years, and certain nematode populations may overcome resistance, depending on density, species, race, and temperature (Engelbrecht *et al.*, 2020). Therefore, repeated screening under diverse conditions is essential prior to variety adoption. Despite these challenges, host resistance remains a key alternative in Africa, particularly if resistant cultivars are accessible and combined with other sustainable practices, such as crop rotation, to reduce dependence on chemical nematicides.

3.2.8.3. Biological agents and root knot nematodes control

The utilization of microorganisms as a biological control method represents a promising approach for managing RKNs. Several studies have demonstrated the effectiveness of this method in Africa.

In Benin, Affokpon *et al.* (2011a) reported an 80% reduction in RKN population densities in roots following treatment with *T. asperellum* T-16, along with an increase of more than 30% in tomato yield. In another experiment conducted in Benin, pre-planting application of some *P. chlamydosporia* isolates led to up to 50% infected eggs and a 25% reduction in RKN multiplication and root galling damage (Affokpon *et al.*, 2015). Affokpon *et al.* (2011b) also reported that field application of arbuscular mycorrhizal fungi reduced nematode population densities and root galling damage. Trudgill *et al.* (2000) highlighted the potential of *P. penetrans* against RKNs in Malawi, Tanzania, Senegal, and Burkina Faso. Reduction of gall numbers by 82% - 86% was observed in tomato under greenhouse conditions in South Africa following the application of five PGPR strains (*Bacillus firmus* T11, *Bacillus aryabhattai* A08, *Paenibacillus barcinonensis* A10, *Paenibacillus alvei* T30, and *Bacillus* *cereus* N10w) (Viljoen *et al.*, 2019). In Egypt, a number of chitinolytic rhizobacteria strains such as *Pseudomonas lini* (isolat AB3), *Lactobacillus helveticus* (isolat AB4) *et Klebsiella oxytoca* (isolat AB5) reduced the gall formation, female numbers, egg-mass production, and final population of juveniles in soil. In another experiment conducted in Egypt, the soil application of *Pichia guilliermondii* ATCC 9058 led to reductions of 89.6%, 90%, and 90% in the number of eggs, egg masses, females, and juveniles (J2s), respectively (Bakr *et al.*, 2024). Similarly, in Kenya, *Trichoderma asperellum* and *Fusarium oxysporum* species complex isolates reduced root-knot nematode egg densities by 35 - 46 % (Bogner *et al.*, 2016). The effectiveness of *Bacillus* in South Africa (Chinheya *et al.*, 2017), *P. penetrans* in Senegal in clay soils (Dabiré *et al.*, 2007), and *Arthrobotrys oligospora* in Egypt (Bakr *et al.*, 2014) has also been documented. Commercial fungal biological control products for nematode management are already available in some African countries, such as South Africa (Abd-Elgawad and Askary, 2018).

3.2.8.4. Biofumigation and root knot nematodes control

Studies on RKN management through biofumigation in Africa have shown promising results. Youssef and Lashein (2013) observed reduced gall numbers when chopped *B. oleracea* leaves were incorporated into the soil before tomato transplanting and nematode inoculation in pots. Similarly, Kruger *et al.* (2015) reported significant suppression of *M. javanica* in South Africa following incorporation of macerated *B. juncea* tissues into nematode-infested soil before tomato planting. In Kenya, Kago *et al.* (2013) showed a significant reduction in nematode populations after the incorporation of chopped cabbage leaves into infested soil before tomato, chili, and potato cultivation. Mashela *et al.* (2017) also observed the suppression of *M. incognita* and increased tomato yield after the incorporation of raw cabbage leaves in South Africa. Muiru *et al.* (2017) reported reductions of 90% and 67% in nematode numbers in green bean cultivation under greenhouse and field conditions, respectively, after the incorporation of *S. alba* and *E. sativa*. Recently, Hassan *et al.* (2020) reported that biofumigation of forage radish reduced galls, egg masses, and J2 in soil by 84%–90% in Egypt. Galadima *et al.* (2025) also demonstrated the efficacy of incorporating cabbage leaves into pots in reducing RKN populations in Nigeria. Abdel-Baset *et al.* (2025) reported that field application of mustard seeds as a biofumigant significantly reduced nematode populations, including galls, egg masses, and second-stage juveniles in Egypt. Maximum reductions of 70.4% and 82.1% were observed when *B. oleracea* and *B. caulorapa* residues were applied 10 days before sowing, respectively (El-Nagdi *et al.*, 2019). El-Sherbiny and Awad Allah (2014) found that pre-planting with air dried powders of several plants, including cauliflower (a crucifer plant), minimized *M. incognita* on tomato plants and increased plant growth.

Biofumigation appears to be an environmentally friendly alternative to chemical fumigation and can produce effects similar to those of synthetic nematicides in several studies. Nevertheless, the inconsistent suppression effect of this method on RKNs populations suggests its combination with other control options, such as crop rotation and biological control. Moreover, biofumigation may negatively affect beneficial soil microbial communities through the uncontrolled release of toxic compounds (Dutta *et al.*, 2019).

3.2.8.5. Organic amendments and root knot nematodes control

Numerous studies in Africa have assessed the efficacy of organic amendments for RKNs management. Hamida *et al.* (2015) reported that the application of compost reduced the population of *M. incognita* by 57%–66% in Egypt. In Kenya, Atandi *et al.* (2017) observed a reduction in field RKNs populations following the application of compost, *Tithonia diversifolia*, and neem cake. Incorporation of plant-based composts in South Africa reduced nematode population densities by 43%–94% (Tefu *et al.*, 2022). Atungwu *et al.* (2009) recorded a 47.9% reduction in the population of *M. incognita* following soil amendment with organic material. Mashela *et al.* (2017) demonstrated that organic amendments, including compost, animal manure, neem powder, and permaculture systems, can significantly reduce *Meloidogyne* spp. populations by up to 99%, with concomitant yield increases of up to 500%. The efficacy varied according to the type of amendment and crop species. Ogaraku (2007) also reported that in Nigeria, potted plants amended with poultry and cattle manure showed resistance to *M. javanica*. Ismail (2015) found that organic composts (banana, maize, sawdust, etc.) were the most effective in reducing *M. javanica* populations and significantly improving sunflower growth. The application of 5% and 7.5% rice straw compost reduced RKN populations by 79% and 84%, respectively, under greenhouse conditions in Egypt (Rashed *et al.*, 2011).

Further studies by Olabiyi and Oladeji (2010), Olabiyi *et al.* (2013), and Olabiyi and Sanusi (2025) showed that organic composts based on neem, cassava peel, sawdust, and *Tithonia* significantly reduced final soil nematode populations and root infections in several field crops, improving growth and yield. Sossou *et al.* (2022) reported that composted manure and microorganism-fermented plant extracts were effective against *M. incognita* in field tomato production in Nigeria, although their combination increased *M. incognita* populations under greenhouse conditions. Oladele *et al.* (2021) also demonstrated the efficacy of biochar in RKNs management in Nigeria. Amulu *et al.* (2018) reported encouraging results on organic amendments for RKN suppression using poultry manure, Fabiyi (2024) using *Blumea aurita* compost, El-Deriny and Hammad (2022) using various composts, Osman *et al.* (2022) using bacteria-enriched composts (*Bacillus cereus*), and Bakr *et al.* (2022) using diverse compost types. Recently, an *in vitro* study by Sero *et al.* (2025) demonstrated the effectiveness of compost teas derived from *Crotalaria retusa* and *Crateva adansonii* against *Meloidogyne enterolobii*, considered the most virulent RKN species, suggesting the need for further greenhouse and field investigations.

4. Conclusion and futures directions

The effective management of crop pests and diseases is crusial for sustainable food production. The control of RKNs has historically been based on the use of agrochemical products (Khder *et al.*, 2025). With the progressive withdrawal of first-line nematicides from global markets and the increasing trend toward organic and sustainable agriculture, research and extension efforts to develop and disseminate information on alternative RKNs management strategies must be strengthened (Dutta *et al.*, 2019). Several alternatives can be considered in the African context.

These include crop rotation, consisting of sequentially planting crops from different families on the same plot to disrupt the RKN life cycle; biofumigation using residues from Brassicaceae and non-Brassicaceae crops; biological control through the use of antagonistic living organisms; the inclusion of nematicidal plants in rotation; plant extracts with pesticidal properties (fungi, bacteria, etc.); the use of resistant cultivars; and the application of organic amendments (compost, animal manure, biochar).

Previous research on each of these alternatives has revealed the limitations associated with each method. Briefly, crop rotations often fail to provide satisfactory results if the rotation crop is poorly chosen and considered uneconomical in intensive systems (Sikora *et al.*, 2023); biofumigation shows variable effects and may negatively impact the beneficial microbial community in the soil; the use of resistant cultivars is often constrained by breeding time, costs, nematode density and species, as well as environmental conditions (temperature, soil moisture); biological control is limited by the selection and deployment of appropriate control agents, environmental conditions, and overall soil health (Afzal and Mukhtar, 2024). Most studies report improvements in crop yields although organic amendments exhibit variable effects depending on the type of amendment. The latter approach appears particularly suitable to the African context, where organic amendments are an integral part of crop production practices. Moreover, these alternatives should be combined to develop an integrated nematode management system to achieve effective RKN management.

Most studies reported in this context have produced relevant and encouraging results. However, the majority of these has been conducted under laboratory and greenhouse conditions. Additionally, the costs of applying certain methods and the time required for their effects often limit their adoption by poor resource farmers in Africa. Furthermore, factors that could constrain the application of research solutions include limited knowledge of RKN biology, particularly among small-scale farmers (Talwana *et al.*, 2016), poor understanding of nematodes among extension agents, which restricts their ability to implement or recommend appropriate management strategies (Coyne *et al.*, 2018), lack of nematology expertise within national research and extension services (Cortada *et al.*, 2019), and low involvement of governments, national programs, and organizations (Talwana *et al.*, 2016).

Although laboratory and greenhouse experiments are necessary to better evaluate each method by eliminating external factors, conducting further field research to assess the effectiveness of these methods is recommended. Future studies should also evaluate the potential of multiple methods to provide farmers with an integrated management program. Considering that factors such as nematode density and species in the soil, soil temperature, and other environmental conditions influence the efficacy of certain methods, multiple trials under varying temperatures and with different RKN species are required. Governments, national programs, and organizations should also subsidize innovative and effective research solutions to ensure that farmers can benefit. Promoting two-way communication between researchers, extension services, and farmers through training and seminars is also essential for effective nematode management. Governments should also regulate the import and use of agrochemical products to support sustainable and environmentally friendly agriculture.

In conclusion, various options as alternatives to exist for managing RKNs, although each has its limitations. To fully harness these alternatives for the better RKNs management in key crops, it is necessary to better understand these limitations and consequently develop an integrated management system.

Competing interests

Authors have declared that no competing interests exist.

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