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Review article

## Global perspectives on medicinal plants and their phytochemicals in the management of major plant-parasitic nematodes (root-knot and cyst)

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### Abstract

Plant-parasitic nematodes (PPNs) are among the most destructive agricultural pests worldwide, causing substantial yield losses in a wide range of agricultural and horticultural crops. Among them, the most economically important are root-knot nematodes (*Meloidogyne* spp.) and cyst nematodes belonging to the genera *Heterodera* and *Globodera*. Although synthetic nematicides have been widely used for their control, their application is increasingly restricted because of concerns regarding environmental pollution, risks to human health, and high costs, leading to growing interest in natural resources, particularly medicinal plants and their phytochemicals, as safe and sustainable alternatives. Over the past few decades, more than 260 medicinal and aromatic plants have been isolated and reported to possess nematocidal activity, and hundreds of bioactive secondary metabolites have been identified, including terpenoids, alkaloids, flavonoids, phenolic acids, saponins, and glucosinolates. These bioactive compounds act through diverse mechanisms, including inhibition of egg hatching, suppression of second-stage juvenile (J2) motility, disruption of cuticle integrity, alteration of membrane permeability, and interference with key metabolic and enzymatic pathways. Notable medicinal plants reported to possess significant nematocidal activity include *Azadirachta indica*, *Tagetes* spp., *Allium sativum*, *Cymbopogon citratus*, *Melia azedarach*, *Brassica* spp., *Ocimum* spp., and *Artemisia* spp. This review provides a global perspective on the use of medicinal plants and their bioactive phytochemicals against root-knot and cyst nematodes, critically evaluates their modes of action, efficacy, and limitations, and discusses their potential role in sustainable nematode management.

**Keywords:** Botanical nematicides, cyst nematodes, medicinal plants, root-knot nematodes, secondary metabolites, sustainable agriculture

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## دیدگاه‌های جهانی درباره گیاهان دارویی و ترکیبات فیتوشیمیایی آن‌ها در مدیریت نماتدهای مهم انگل گیاهی (ریشه‌گرهی و سیستی)

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### چکیده

نماتدهای انگل گیاهی یکی از مهم‌ترین و مخرب‌ترین عوامل خسارت‌زای کشاورزی در جهان هستند و موجب کاهش قابل توجه عملکرد طیف وسیعی از محصولات زراعی و باغی می‌شوند. در بین آن‌ها، نماتدهای ریشه‌گرهی (*Meloidogyne spp.*) و نماتدهای سیستی متعلق به جنس‌های *Heterodera* و *Globodera* دارای اهمیت فراوان می‌باشند. اگرچه نماتدکشی‌های شیمیایی سال‌ها به‌طور گسترده برای مهار این نماتدها مورد استفاده قرار گرفته‌اند، کاربرد آن‌ها به دلیل نگرانی‌های زیست‌محیطی، خطرات برای سلامت انسان و هزینه‌های بالا به‌طور فزاینده‌ای محدود شده است و توجه پژوهشگران به استفاده از منابع طبیعی، به‌ویژه گیاهان دارویی و ترکیبات فیتوشیمیایی آن‌ها، به عنوان جای‌گزین ایمن و پایدار افزایش یافته است. تاکنون بیش از ۲۶۰ گونه گیاه دارویی و معطر با خاصیت نماتدکشی گزارش شده‌اند. مطالعات فیتوشیمیایی این گیاهان منجر به جداسازی و شناسایی صدها متابولیت ثانویه زیست‌فعال شامل ترپنوئیدها، آلکالوئیدها، فلاونوئیدها، اسیدهای فنولی، ساپونین‌ها و گلوکوزینولات‌ها شده است. این ترکیبات از طریق سازوکارهای متعددی نظیر مهار تغریخ تخم، کاهش تحرک لاروهای سن دو نماتد، تخریب ساختار کوتیکول و ایجاد اختلال در مسیرهای متابولیکی و آنزیمی حیاتی نماتدها، اثرات نماتدکشی خود را اعمال می‌کنند. از جمله مهم‌ترین گیاهان دارویی گزارش‌شده با فعالیت نماتدکشی می‌توان به چریش (*Azadirachta indica*)، گل جعفری (*Tagetes spp.*)، سیر (*Allium sativum*)، علف لیمو (*Cymbopogon citratus*)، زیتون تلخ (*Melia azedarach*)، انواع کلم (*Brassica spp.*)، انواع ریحان (*Ocimum spp.*) و درمنه (*Artemisia spp.*) اشاره کرد. این مقاله با ارائه چشم‌اندازی جهانی، کاربرد گیاهان دارویی و ترکیبات فیتوشیمیایی زیست‌فعال آن‌ها علیه نماتدهای ریشه‌گرهی و سیستی را مرور کرده، سازوکارهای اثر، کارایی و محدودیت‌های آن‌ها را به‌صورت انتقادی ارزیابی می‌کند و نقش بالقوه این منابع طبیعی را در مدیریت پایدار نماتدها مورد بحث قرار می‌دهد.

**واژه‌های کلیدی:** کشاورزی پایدار، گیاهان دارویی، متابولیت‌های ثانویه، نماتدهای ریشه‌گرهی، نماتدهای سیستی و نماتدکشی‌های گیاهی

## Introduction

Plant-parasitic nematodes (PPNs) represent one of the most significant constraints to global agricultural productivity, with annual crop losses estimated to exceed 100 billion US Dollars (Jones *et al.* 2013). These obligate parasites are widely distributed and infect a broad range of crops in both temperate and tropical regions. Among the most economically important PPNs are root-knot nematodes (*Meloidogyne* spp.; RKNs) and cyst nematodes (*Heterodera* spp. and *Globodera* spp.), which are among the dominant plant-parasitic nematode groups in many agricultural soils worldwide (Jones *et al.* 2013). Both groups are sedentary endoparasites that establish specialized feeding sites within host roots, making their management particularly challenging. Other economically important PPNs include *Pratylenchus* spp. (lesion nematodes), *Rotylenchulus reniformis* (reniform nematode), *Radopholus similis* (burrowing nematode), *Nacobbus aberrans* (false root-knot nematode), *Xiphinema* spp. (dagger nematodes), *Longidorus* spp. (needle nematodes), and *Tylenchulus semipenetrans* (citrus nematode) (Sikora & Fernández 2005).

RKNs parasitize more than 2,000 plant species and are estimated to account for approximately 5% of global crop yield losses. They induce characteristic root knots, disrupt water and nutrient transport, and predispose plants to secondary infections by soilborne pathogens (Chitwood 2003). In contrast, cyst nematodes produce durable cysts that encase their eggs, enabling long-term survival in soil and complicating eradication efforts. Their evolutionary adaptations, including dormancy and host-induced hatching mechanisms, make them particularly challenging to manage. Historically, chemical nematicides such as carbamates and organophosphates have served as the primary management strategy. However, their use is increasingly restricted due to environmental persistence, high toxicity, and detrimental effects on non-target organisms (Ntalli & Caboni 2012). In addition, the withdrawal of many conventional nematicides from the market has intensified the search for environmentally acceptable alternatives. Consequently, there is growing interest in sustainable and eco-friendly alternatives, particularly plant-derived nematicides and medicinal plant-based products for integrated nematode management (Forghani & Hajihassani 2020).

Medicinal and aromatic plants constitute a promising source of bioactive compounds with nematocidal activity. More than 260 medicinal and aromatic plant species have been reported to possess nematocidal activity, and phytochemical investigations have identified structurally diverse secondary metabolites, including terpenoids, alkaloids, flavonoids, phenolic acids, saponins, and glucosinolates (Ntalli & Caboni 2012; Ibrahim *et al.* 2024). The structural diversity of these phytochemicals contributes to their broad spectrum of nematocidal activities and may reduce the risk of resistance development compared with single-target synthetic nematicides. Representative bioactive compounds include azadirachtin from *Azadirachta indica*, thiophenes from *Tagetes* spp., allicin from *Allium sativum*, limonene and citral from *Cymbopogon citratus*, and triterpenoids from *Melia azedarach* (Ntalli & Caboni 2012). These compounds exert their nematocidal activity through multiple mechanisms, including inhibition of egg hatching, suppression of the motility and infectivity of second-stage juveniles (J2s), disruption of cuticle integrity, alteration of membrane permeability, and interference with key metabolic and enzymatic pathways (Ntalli & Caboni 2012; Ibrahim *et al.* 2024).

Building upon these findings, recent advances have highlighted the increasing importance of botanical products in sustainable nematode management. For example, essential oils from Mediterranean aromatic plants have demonstrated more than 80% mortality of J2s and strong inhibition of *Meloidogyne javanica* egg hatching (Ferreira *et al.* 2025). The integration of botanicals with microbial biocontrol agents and organic amendments has shown suppression levels comparable to those of chemical nematicides in microplot studies (Machal *et al.* 2025). In addition, nanoformulations and controlled-release systems are being developed to enhance the stability and field efficacy of phytochemicals (Kamaraj *et al.* 2024). Despite these promising developments, challenges related to formulation stability, cost-effectiveness, large-scale production, and field validation remain important obstacles to the commercialization of botanical nematicides.

At the molecular level, sedentary endoparasitic nematodes (RKNs and cyst nematodes) secrete effector proteins that suppress host immunity and manipulate host cellular and metabolic pathways to establish and maintain specialized feeding sites. Notably, some

phytochemicals have been reported to interfere with nematode effector activity or to enhance host defense signaling, thereby contributing to the indirect suppression of nematode infection. Given their global distribution, economic impact, and distinct biological strategies, RKNs and cyst nematodes warrant particular attention. Accordingly, this review aims to (i) provide a comprehensive overview of medicinal plants and their bioactive phytochemicals with nematicidal properties, (ii) critically evaluate their mechanisms of action, and (iii) discuss their potential role in sustainable nematode management and integrated pest management (IPM) programs.

## Materials and Methods

This review provides a comprehensive synthesis of the scientific literature on plant-parasitic nematodes (PPNs), medicinal and aromatic plants with nematicidal activity, and their bioactive secondary metabolites. The objective was to identify, synthesize, and critically evaluate the most relevant peer-reviewed studies to provide a comprehensive overview of plant-derived nematicidal agents, their mechanisms of action, and their potential applications in sustainable nematode management.

### Literature search strategy

Electronic databases, including Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar, were comprehensively searched for peer-reviewed articles published between 1980 and 2025. Search strategies combined relevant keywords and Boolean operators, including “plant-parasitic nematodes”, “root-knot nematodes”, “cyst nematodes”, “nematicidal plants”, “botanical nematicides”, “phytochemicals”, “secondary metabolites”, “essential oils”, “natural products”, and representative plant species such as *Azadirachta indica*, *Tagetes* spp., *Allium sativum*, *Cymbopogon citratus*, and *Melia azedarach* (Ntalli & Caboni 2012; Ibrahim *et al.* 2024). Searches were limited to peer-reviewed articles published in English and, where necessary, Persian. In addition, backward citation tracking and manual screening of the reference lists of key publications were performed to identify additional relevant studies.

## Inclusion and exclusion criteria

### Inclusion criteria

Studies reporting the nematicidal or nematostatic activity of medicinal and aromatic plants or other botanicals against economically important plant-parasitic nematodes (e.g., root-knot and cyst nematodes) (Jones *et al.* 2013; Ntalli & Caboni 2012).

Studies reporting the chemical identification of bioactive secondary metabolites responsible for the observed nematicidal activity (Ibrahim *et al.* 2024).

Experimental studies conducted under *in vitro*, greenhouse, or field conditions, with quantifiable biological outcomes (e.g., egg hatching inhibition, J2 mortality, reproduction factor, and motility reduction) (Forghani & Hajihassani 2020; Machal *et al.* 2025).

Articles published in peer-reviewed journals in English and, where necessary, Persian.

Duplicate publications reporting the same experimental data were considered only once.

Studies emphasizing environmental safety and compatibility with integrated pest management

(IPM) programs were prioritized in the synthesis.

### Exclusion criteria

Studies without clear methodological descriptions (e.g., extraction method, concentration, or exposure duration) (Ntalli & Caboni 2012).

Reports presenting only computational predictions without experimental validation.

Non-peer-reviewed publications, conference abstracts, or proceedings with insufficient experimental data.

Studies with incomplete reporting (e.g., absence of appropriate controls, insufficient replication, or lack of statistical analysis).

### Data extraction and synthesis

Data were extracted systematically from each eligible study. The following information was collected:

Target plant-parasitic nematode species, with particular emphasis on root-knot and cyst nematodes.

Plant species and plant part(s) evaluated (e.g., leaves, roots, seeds, or flowers).

Type of botanical preparation or formulation (e.g., essential oil, solvent extract, crude extract, purified fraction, or nanoformulations).

Identified bioactive secondary metabolites and their chemical classes (e.g., terpenoids, alkaloids, phenolics, glucosinolates, and flavonoids).

Experimental conditions (*in vitro*, greenhouse, or field trials).

Measured biological responses and proposed mechanisms of action, including inhibition of egg hatching, J2 mortality, reduction of motility, suppression of reproduction, and interference with physiological or biochemical processes (Ntalli & Caboni 2012; Ferreira *et al.* 2025).

Extracted data were carefully checked for accuracy and consistency prior to qualitative synthesis. Patterns, trends, and knowledge gaps across plant taxa, metabolite classes, formulation types, experimental systems, and target nematode groups were critically evaluated. The synthesized findings were organized into summary tables and, where appropriate, figures to facilitate comparisons of the relative efficacy of different plant species, botanical products, and bioactive compounds.

### Quality assessment

The methodological quality of the selected studies was assessed based on the following criteria: experimental design, replication, sample size, detailed description of extraction procedures and compound identification methods, use of appropriate controls, application of appropriate statistical analyses, and transparent reporting of results (Forghani & Hajihassani 2020; Ibrahim *et al.* 2024). When available, declarations of funding sources and potential conflicts of interest were also considered to aid interpretation of the reported findings.

### Reporting guidelines

To enhance transparency and reproducibility, this review was conducted following principles aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, including explicit reporting of the literature search strategy, study selection process, eligibility criteria, data extraction, and qualitative synthesis (Moher *et al.* 2009; Ferreira *et al.* 2025). A flow diagram was prepared to illustrate the numbers of records identified, screened, excluded, and ultimately included in the review. Following the screening process, 98 publications met the predefined eligibility criteria and were included in the final qualitative synthesis.

## Results

### Overview of the retrieved studies

Following the screening process, a total of 98 publications were included in the review. These studies encompassed 52 medicinal plant families, 117 plant species, and 28 classes of bioactive metabolites investigated against root-knot nematodes (*Meloidogyne* spp.) and cyst nematodes (*Heterodera* spp. and *Globodera* spp.). The retrieved data are summarized in Tables 1–9 and Figures 1–3.

### Medicinal plants effective against root-knot nematodes

Root-knot nematodes (*Meloidogyne javanica* and *M. incognita*) were the most extensively investigated target species among the retrieved studies. Numerous medicinal plants representing diverse botanical families were evaluated for their nematicidal activity using various plant parts and formulations, including powders, aqueous and organic solvent extracts, essential oils, purified fractions, and nanoformulations. The most common biological endpoint reported across studies was the reduction in J2 motility, followed by egg hatching inhibition, impair nematode development and mobility, and suppress reproduction. Detailed information on the investigated plant species, plant parts, extraction methods, application concentrations, bioactive compounds, and observed biological activities is presented in Tables 1 and 2.

### Medicinal plants effective against cyst nematodes

Studies targeting cyst nematodes included economically important species of *Heterodera* (*H. avenae*, *H. schachtii*, *H. filipjevi*, *H. latipons*, *H. glycines*) and *Globodera* (*G. rostochiensis* and *G. pallida*). A wide range of medicinal plants from diverse botanical families was evaluated using different plant parts, extraction methods, and formulations. Across the reviewed studies, botanical products were reported to exhibit nematicidal or nematostatic activity by reducing egg hatching, suppressing J2 survival and development, limiting root invasion, and decreasing nematode reproduction. Detailed information on the investigated plant species, plant parts, extraction methods, application concentrations, bioactive compounds, and observed biological activities is presented in Tables 3–9.

### Distribution of botanical formulations

*Meliaceae*, *Lamiaceae*, *Asteraceae*, and *Fabaceae* were the most frequently represented plant families among the reviewed studies.

Essential oils were the most frequently used botanical formulation (36%), followed by plant powders (30%) and

aqueous extracts (26%). Organic solvent extracts were reported less frequently, with methanolic and ethanolic extracts accounting for 4% and 1% of reviewed studies, respectively. Other formulations, including ash, tannin extracts, combined powder-essential oil preparation, and foliar spray, each represented less than 1% of the reviewed studies (Figure 1).

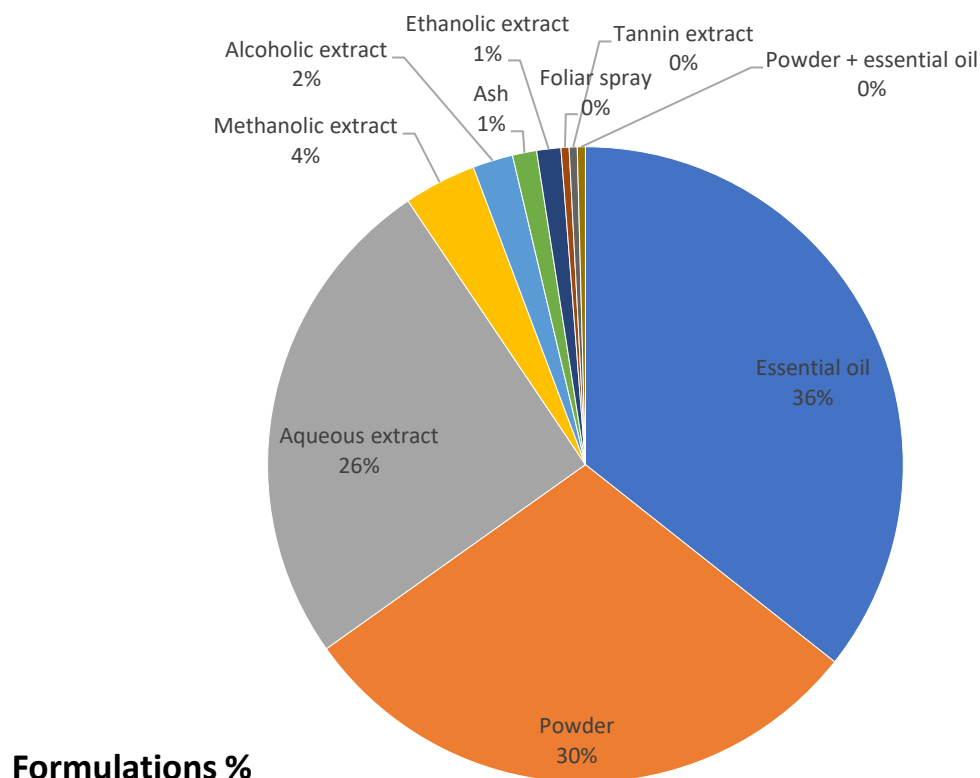


**Figure 1.** Percentage distribution of botanical formulations used for the management of Plant-parasitic nematodes.

### Plant parts

Aerial parts (38.9%) and leaves (33.2%) were the most frequently used plant parts for the management of plant-parasitic nematodes. Flowers and whole plants each accounted for 4.1% of the retrieved studies, followed by fruits and seeds (3.3% each) and shoot tips (1.6%). The remaining studies (11.5%) evaluated other plant materials, including roots, bark, or mixed plant tissues (Figure 2).

### Major bioactive compounds

Among the bioactive compounds identified across the reviewed studies, menthol and menthone, together with thymol and carvacrol, were the most frequently reported

compounds, followed by azadirachtin, anethole, and fenchone (Figure 3).

## Discussion

### Phylogenetic distribution of nematicidal plant families

The predominance of a limited number of botanical families among the retrieved studies suggests that nematicidal activity is not randomly distributed across the plant kingdom but is concentrated within specific evolutionary lineages characterized by the production of diverse bioactive secondary metabolites.

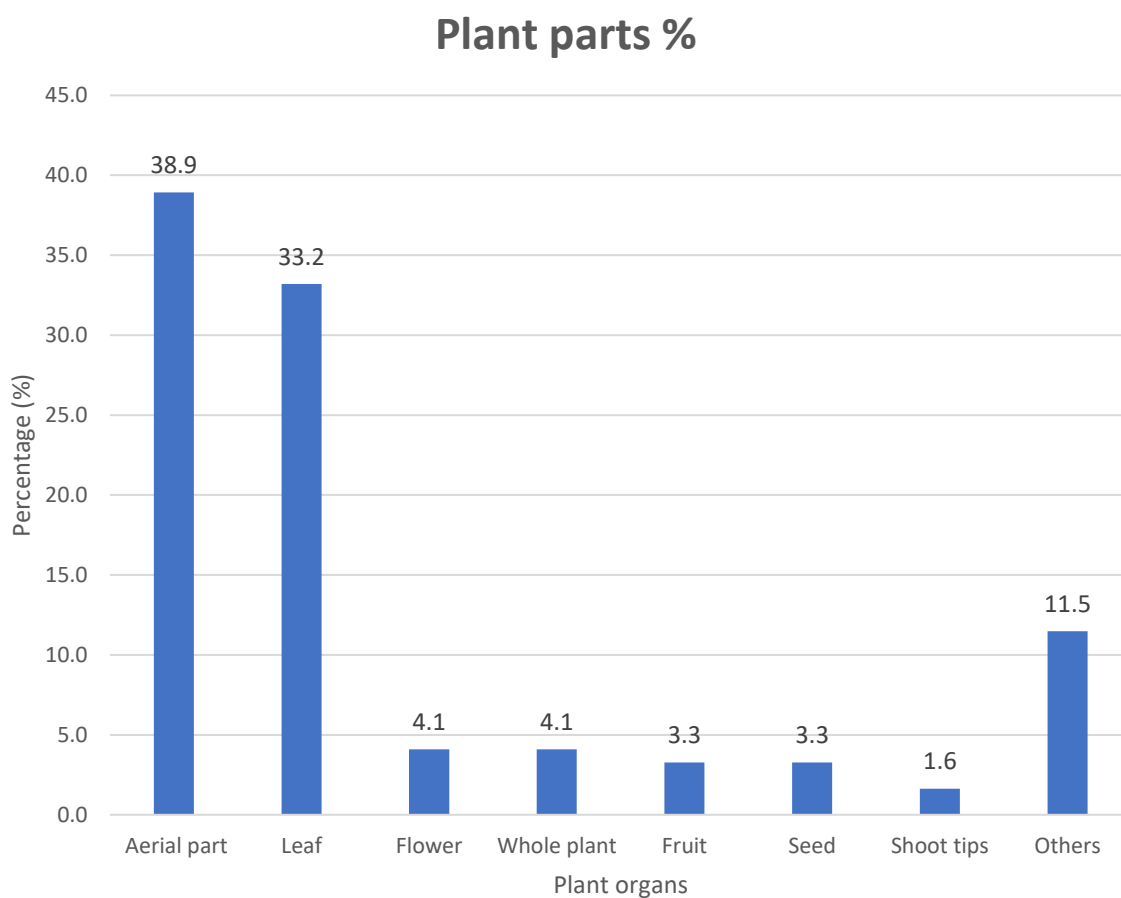


**Figure 2.** Percentage distribution of plant organs used for the management of plant-parasitic nematodes.

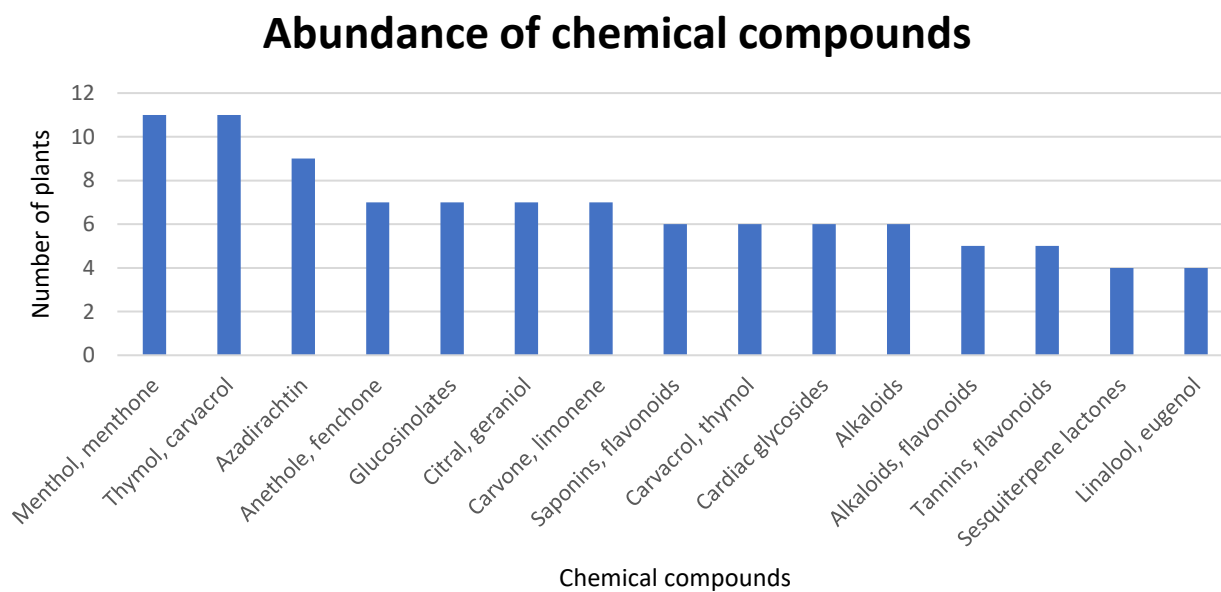


**Figure 3.** The most frequently reported phytochemicals associated with nematocidal activity.

This phylogenetic pattern indicates that closely related plant taxa may share conserved biosynthetic pathways responsible for the synthesis of compounds with nematicidal activity, providing a useful framework for future bioprospecting and the discovery of novel botanical nematicides.

Among the most frequently represented families, the *Meliaceae* (e.g. *Azadirachta indica* and *Melia azedarach*) are characterized by a rich diversity of limonoids and other terpenoids, particularly azadirachtin and related compounds, which exhibit multiple modes of action, including inhibition of egg hatching, J2 mortality, disruption of nematode development, and suppression of reproduction. Similarly, members of the *Lamiaceae* (e.g. *Mentha* spp., *Thymus* spp., and *Ocimum* spp.) are rich in monoterpenes and phenolic constituents, such as thymol, carvacrol, menthol, and menthone, which are widely recognized for their strong nematicidal activity.

Members of the *Asteraceae* (e.g. *Tagetes* spp. and *Artemisia* spp.) contain sesquiterpene lactones, flavonoids, and other bioactive metabolites that contribute to nematode suppression through multiple physiological and biochemical mechanisms. Likewise, species of the *Fabaceae* (e.g. *Crotalaria* spp. and *Cassia* spp.) produce alkaloids and saponins that interfere with nematode growth and reproduction, whereas members of the *Amaryllidaceae*, particularly *Allium* spp., synthesize sulfur-containing compounds such as allicin that have demonstrated pronounced activity against cyst nematodes.

The repeated occurrence of these families across independent studies is unlikely to be explained solely by research bias but rather reflects their inherent capacity to produce chemically diverse metabolites with broad-spectrum nematicidal properties. Moreover, many of these families have long been utilized in traditional medicine and crop protection, further supporting the close relationship between phytochemical diversity and nematicidal activity. Although these families belong to distinct evolutionary lineages, they converge in their ability to produce chemically diverse secondary metabolites with nematicidal activity, suggesting that different biosynthetic pathways may have evolved toward a common ecological function of defense against PPNs.

Collectively, these findings indicate that phylogenetically informed selection of medicinal plants

represents a promising strategy for identifying new sources of natural nematicides. Future research should therefore prioritize comparative investigations within these high-potential families while also exploring underrepresented taxa that may harbor novel bioactive metabolites with complementary modes of action.

### Plant organs as sources of bioactive compounds

Aerial parts and leaves together accounted for more than two-thirds of all reported plant organs used in the reviewed studies, highlighting their importance as major reservoirs of nematicidal phytochemicals. Their predominance is likely attributable not only to their high concentrations of secondary metabolites, including terpenoids, phenolics, and alkaloids, but also to their ease of collection, renewability, and suitability for large-scale extraction. In contrast, underground organs such as roots and bulbs were investigated less frequently despite accumulating unique bioactive compounds with demonstrated nematicidal properties in certain plant taxa. This uneven distribution suggests that research has largely focused on readily accessible aerial tissues, while the nematicidal potential of less frequently studied organs remains underexplored. Future comparative studies evaluating the phytochemical composition and bioactivity of different plant organs within the same species may facilitate the identification of more promising sources of natural nematicides.

### Chemical diversity and mechanisms of action

Among the identified phytochemicals, azadirachtin, carvacrol, thymol, as well as flavonoids and alkaloids, were among the compounds most frequently associated with strong nematicidal activity. Azadirachtin, derived from *Azadirachta indica*, exhibited both larvicidal and ovicidal activity, making it a promising candidate for broad-spectrum nematode control owing to its ability to affect multiple stages of the nematode life cycle. These compounds exert their nematicidal effects through diverse physiological and biochemical mechanisms, including disruption of membrane integrity, induction of oxidative stress, neurotoxic effects, and interference with egg development. Owing to their multicomponent composition, essential oils can simultaneously affect multiple molecular targets, thereby reducing the likelihood of resistance development in nematode populations. Moreover, the toxicity of individual essential oils and their constituents vary considerably

**Table 1.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Meloidogyne javanica*.

| Plant species                 | Plant part      | Botanical formulation | Concentration      | Major bioactive compounds     | Ref.                             |
|-------------------------------|-----------------|-----------------------|--------------------|-------------------------------|----------------------------------|
| <i>Anagyris foetida</i>       | Leaf & Fruit    | Powder                | 20 µg/mL           | Alkaloids, flavonoids         | Al-Banna <i>et al.</i> 2003      |
| <i>Artemisia herba-alba</i>   | Leaf            | Powder                | 20 µg/mL           | Artemisinin, flavonoids       | Al-Banna <i>et al.</i> 2003      |
| <i>Artemisia judaica</i>      | Aerial          | Essential oil         | 1000 µL/L          | Camphor, thujone              | Oka <i>et al.</i> 2000           |
| <i>Azadirachta indica</i>     | Seed & Leaf     | Powder                | 30 mL / 250 g soil | Azadirachtin, limonoids       | Moosavi 2012                     |
| <i>Azadirachta indica</i>     | Leaf            | Powder                | 2 g/kg soil        | Azadirachtin, limonoids       | Agbenin <i>et al.</i> 2004       |
| <i>Carthamus glaucus</i>      | Seed            | Powder                | 30 mL / 250 g soil | Saponins, flavonoids          | Moosavi 2012                     |
| <i>Carum carvi</i>            | Aerial          | Essential oil         | 100–200 mg/kg soil | Carvone, limonene             | Oka <i>et al.</i> 2000           |
| <i>Carum carvi</i>            | Aerial          | Essential oil         | 800 µL/L           | Carvone, limonene             | Oka <i>et al.</i> 2000           |
| <i>Citrus sinensis</i>        | Leaf            | Powder                | 121 ppm            | Flavonoids, limonoids         | Ibrahim <i>et al.</i> 2006       |
| <i>Coridothymus capitatus</i> | Aerial          | Essential oil         | 1000 µL/L          | Carvacrol, thymol             | Oka <i>et al.</i> 2000           |
| <i>Cymbopogon citratus</i>    | Aerial          | Essential oil         | 1000 µL/L          | Citral, geraniol              | Oka <i>et al.</i> 2000           |
| <i>Cymbopogon flexuosus</i>   | Aerial          | Essential oil         | 4000 µg/mL         | Citral, limonene              | Sangwan <i>et al.</i> 1985       |
| <i>Cymbopogon martini</i>     | Aerial          | Essential oil         | 4000 µg/mL         | Citral, geraniol              | Sangwan <i>et al.</i> 1985       |
| <i>Cymbopogon winterianus</i> | Aerial          | Essential oil         | 4000 µg/mL         | Citronellal, geraniol         | Sangwan <i>et al.</i> 1985       |
| <i>Datura metel</i>           | Seed & Leaf     | Powder                | 30 mL / 250 g soil | Tropane alkaloids             | Moosavi 2012                     |
| <i>Datura stramonium</i>      | Aerial          | Methanolic ext.       | 10%                | Tropane alkaloids             | Fayyaz 2014                      |
| <i>Dorema ammoniacum</i>      | Aerial          | Essential oil         | 4000 ppm           | Coumarins, sesquiterpenes     | Rouhani <i>et al.</i> 2014       |
| <i>Eucalyptus</i> spp.        | Aerial          | Essential oil         | 4000 ppm           | 1,8-cineole, $\alpha$ -pinene | Rouhani <i>et al.</i> 2014       |
| <i>Eupatorium viscidum</i>    | Aerial          | Essential oil         | 1 µg/µL            | Sesquiterpenes                | Sosa <i>et al.</i> 2012          |
| <i>Euphorbia macroclada</i>   | Leaf            | Powder                | 20 µg/mL           | Diterpenoids                  | Al-Banna <i>et al.</i> 2003      |
| <i>Euphorbia macroclada</i>   | Leaf            | Powder                | 20 µg/mL           | Diterpenoids                  | Al-Banna <i>et al.</i> 2003      |
| <i>Ferula assa-foetidae</i>   | Stem & Root sap | Aqueous ext.          | 2000 ppm           | Sulfur-containing compounds   | Sholevar Fard <i>et al.</i> 2012 |
| <i>Ferula galbanifula</i>     | Aerial          | Essential oil         | 4000 ppm           | Sesquiterpenes                | Rouhani <i>et al.</i> 2014       |
| <i>Ferula hermonis</i>        | Root            | Powder                | 20 µg/mL           | Coumarins, terpenoids         | Al-Banna <i>et al.</i> 2003      |

Table 1. Continued (1).

| Plant species                    | Plant part    | Botanical formulation | Concentration      | Major bioactive compounds                   | Ref.                          |
|----------------------------------|---------------|-----------------------|--------------------|---------------------------------------------|-------------------------------|
| <i>Foeniculum vulgare</i>        | Aerial        | Essential oil         | 100–200 mg/kg soil | Anethole, fenchone                          | Oka <i>et al.</i> 2000        |
| <i>Foeniculum vulgare</i>        | Umbelliferous | Essential oil         | 800 µL/L           | Anethole, fenchone                          | Oka <i>et al.</i> 2000        |
| <i>Foeniculum vulgare</i>        | Umbelliferous | Essential oil         | 800 µL/L           | Anethole, fenchone                          | Oka <i>et al.</i> 2000        |
| <i>Foeniculum vulgare</i>        | Leaf          | Aqueous ext.          | 100 ppm            | Anethole, fenchone                          | Ghobadi <i>et al.</i> 2017    |
| <i>Foeniculum vulgare</i>        | Aerial        | Aqueous ext.          | 40%                | Anethole, fenchone                          | Dolatabadi <i>et al.</i> 2016 |
| <i>Glebionis coronaria</i>       | Flowers       | Powder                | 30 mL / 250 g soil | Sesquiterpene lactones                      | Moosavi 2012                  |
| <i>Gundelia tournefortii</i>     | Whole plant   | Powder                | 20 µg/mL           | Sesquiterpenes                              | Al-Banna <i>et al.</i> 2003   |
| <i>Haplophyllum tuberculatum</i> | Aerial        | Essential oil         | 12.5 µg/mL         | Alkaloids, flavonoids                       | Onifade <i>et al.</i> 2008    |
| <i>Hypericum androsaemum</i>     | Whole plant   | Powder                | 20 µg/mL           | Hypericin, flavonoids                       | Al-Banna <i>et al.</i> 2003   |
| <i>Hyssopus officinalis</i>      | Aerial        | Methanolic ext.       | 10%                | Volatile oils, flavonoids                   | Fayyaz & Fadaei Tehrani 2013  |
| <i>Inula viscosa</i> Greuter     | Leaf          | Powder                | 0.1% w/w           | Sesquiterpene lactones                      | Oka <i>et al.</i> 2000        |
| <i>Lepidium sativum</i>          | Seed          | Essential oil         | 500–1000 ppm       | Benzyl isothiocyanate (from glucosinolates) | El-Habashy 2024               |
| <i>Lepidium sativum</i>          | Fruit         | Powder                | 20 µg/mL           | Glucosinolates                              | Al-Banna <i>et al.</i> 2003   |
| <i>Mentha arvensis</i>           | Aerial        | Essential oil         | 0.291 mg/mL        | Menthol, menthone                           | Andrés <i>et al.</i> 2012     |
| <i>Mentha piperita</i>           | Leaf          | Essential oil         | 250–1000 ppm       | Menthol, Menthone                           | El-Habashy 2024               |
| <i>Mentha rotundifolia</i>       | Aerial        | Essential oil         | 100–200 mg/kg soil | Menthol, menthone                           | Oka <i>et al.</i> 2000        |
| <i>Mentha rotundifolia</i>       | Aerial        | Essential oil         | 800 µL/L           | Menthol, menthone                           | Oka <i>et al.</i> 2000        |
| <i>Mentha rotundifolia</i>       | Aerial        | Essential oil         | 0.204 mg/mL        | Menthol, menthone                           | Andrés <i>et al.</i> 2012     |
| <i>Mentha spicata</i>            | Aerial        | Essential oil         | 100–200 mg/kg soil | Carvone, limonene                           | Oka <i>et al.</i> 2000        |
| <i>Mentha spicata</i>            | Aerial        | Essential oil         | 800 µL/L           | Carvone, limonene                           | Oka <i>et al.</i> 2000        |
| <i>Mentha spicata</i>            | Aerial        | Essential oil         | 0.293 mg/mL        | Carvone, limonene                           | Andrés <i>et al.</i> 2012     |
| <i>Nerium oleander</i>           | Flower        | Powder                | 30 mL / 250 g soil | Cardiac glycosides                          | Moosavi 2012                  |
| <i>Nerium oleander</i>           | Leaf          | Aqueous ext.          | 200 ppm            | Cardiac glycosides                          | Rahmani <i>et al.</i> 2016    |
| <i>Nerium oleander</i>           | Leaf          | Aqueous ext.          | 200 ppm            | Cardiac glycosides                          | Rahmani <i>et al.</i> 2016    |

Table 1. Continued (2).

| Plant species                    | Plant part   | Botanical formulation | Concentration      | Major bioactive compounds           | Ref.                              |
|----------------------------------|--------------|-----------------------|--------------------|-------------------------------------|-----------------------------------|
| <i>Nigella sativa</i>            | Seed         | Aqueous ext.          | 2000 ppm           | Thymoquinone, alkaloids             | Sholeh Varfard <i>et al.</i> 2012 |
| <i>Olea europaea</i>             | Leaf         | Powder                | 30 mL / 250 g soil | Oleuropein                          | Moosavi 2012                      |
| <i>Origanum syriacum</i>         | Aerial       | Essential oil         | 100–200 mg/kg soil | Carvacrol, thymol                   | Oka <i>et al.</i> 2000            |
| <i>Origanum vulgare</i>          | Aerial       | Essential oil         | 100–200 mg/kg soil | Thymol, carvacrol                   | Oka <i>et al.</i> 2000            |
| <i>Peganum harmala</i>           | Seed         | Aqueous ext.          | 2000 ppm           | Alkaloids (harmine, harmaline)      | Sholeh Varfard <i>et al.</i> 2012 |
| <i>Pimpinella anisum</i>         | Fruit        | Powder                | 20 µg/mL           | Anethole                            | Al-Banna <i>et al.</i> 2003       |
| <i>Pimpinella anisum</i>         | Fruit        | Powder                | 20 µg/mL           | Anethole                            | Al-Banna <i>et al.</i> 2003       |
| <i>Plectranthus cylindraceus</i> | Aerial       | Essential oil         | 12.5 µg/mL         | Terpenoids                          | Onifade <i>et al.</i> 2008        |
| <i>Portulaca oleracea</i>        | Seed         | Aqueous ext.          | 2000 ppm           | Saponins, flavonoids                | Sholeh Varfard <i>et al.</i> 2012 |
| <i>Quercus brantii</i>           | Leaf & Fruit | Aqueous ext.          | 5–7%               | Tannins, phenolics                  | Hashemi <i>et al.</i> 2017        |
| <i>Ridolfia segetum</i>          | Aerial       | Essential oil         | 8–32 µL/mL         | β-Pinene (major), α-Pinene, Myrcene | Sarri <i>et al.</i> 2024          |
| <i>Satureja montana</i>          | Aerial       | Essential oil         | 0.041 mg/mL        | Thymol, carvacrol                   | Andrés <i>et al.</i> 2012         |
| <i>Satureja montana</i>          | Aerial       | Methanolic ext.       | 10%                | Thymol, carvacrol                   | Fayyaz & Fadaei Tehrani 2013      |
| <i>Solanum nigrum</i>            | Seed         | Aqueous ext.          | 10%                | Glycoalkaloids                      | Fayyaz 2014                       |
| <i>Thea sinensis</i>             | Leaf         | Powder                | 20 µg/mL           | Catechins, tannins                  | Al-Banna <i>et al.</i> 2003       |
| <i>Thymus capitatus</i>          | Aerial       | Essential oil         | 100–200 mg/kg soil | Thymol, carvacrol                   | Oka <i>et al.</i> 2000            |
| <i>Thymus mastichina</i>         | Aerial       | Essential oil         | 0.300 mg/mL        | Thymol, carvacrol                   | Andrés <i>et al.</i> 2012         |
| <i>Thymus vulgaris</i>           | Aerial       | Pure compound         | 62.5–1000 µL/L     | Thymol (monoterpene phenol)         | Nasiou & Giannakou 2023           |
| <i>Thymus vulgaris</i>           | Aerial       | Essential oil         | 0.224 mg/mL        | Thymol, carvacrol                   | Andrés <i>et al.</i> 2012         |
| <i>Thymus vulgaris</i>           | Aerial       | Methanolic ext.       | 10%                | Thymol, carvacrol                   | Fayyaz & Fadaei Tehrani 2013      |
| <i>Thymus zygis</i>              | Aerial       | Essential oil         | 0.226 mg/mL        | Thymol, carvacrol                   | Andrés <i>et al.</i> 2012         |
| <i>Varthemia iphionoides</i>     | Leaf         | Powder                | 20 µg/mL           | Volatile oils, flavonoids           | Al-Banna <i>et al.</i> 2003       |
| <i>Zingiber officinale</i>       | Rhizome      | Essential oil         | 250–1000 ppm       | Gingerols, Shogaols                 | El-Habashy 2024                   |

**Table 2.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Meloidogyne incognita*.

| Plant species                   | Plant part | Botanical formulation | Concentration                    | Major bioactive compounds  | Ref.                          |
|---------------------------------|------------|-----------------------|----------------------------------|----------------------------|-------------------------------|
| <i>Acorus calamus</i>           | Root       | Powder                | 3.11 µg/mL                       | β-Asarone, sesquiterpenes  | Djiwanti <i>et al.</i> 2009   |
| <i>Aegle marmelos</i>           | Fruit      | Aqueous ext.          | 100 ppm                          | Alkaloids, coumarins       | Patel <i>et al.</i> 2004      |
| <i>Agastache rugosa</i>         | Aerial     | Essential oil         | 3.47 g/mL                        | Estragole, methyl chavicol | Li <i>et al.</i> 2013         |
| <i>Alcornia latifolia</i>       | Leaf       | Ash                   | 3 g/kg soil                      | Mineral salts              | Ononuju & Kpadobi 2008        |
| <i>Alstonia scholaris</i>       | Flower     | Aqueous ext.          | 10%                              | Alkaloids                  | Pandey <i>et al.</i> 2001     |
| <i>Annona squamosa</i>          | Fruit      | Aqueous ext.          | 100 ppm                          | Acetogenins                | Patel <i>et al.</i> 2004      |
| <i>Argemone mexicana</i>        | Flower     | Aqueous ext.          | 10%                              | Alkaloids                  | Pandey <i>et al.</i> 2001     |
| <i>Argemone mexicana</i>        | Leaf       | Aqueous ext.          | 5%                               | Alkaloids                  | Patel <i>et al.</i> 2004      |
| <i>Artemisia annua</i>          | Leaf       | Alcoholic ext.        | 500 ppm                          | Artemisinin, flavonoids    | Katooli <i>et al.</i> 2011    |
| <i>Aster sedifolia</i>          | Leaf       | Aqueous ext.          | 0.5–1 g/100 cm <sup>3</sup> soil | Polyphenols                | Di Vito <i>et al.</i> 2009    |
| <i>Azadirachta indica</i>       | Leaf       | Aqueous ext.          | 10%                              | Azadirachtin               | Singh <i>et al.</i> 2001      |
| <i>Azadirachta indica</i>       | Leaf       | Aqueous ext.          | 5%                               | Azadirachtin               | Patel <i>et al.</i> 2004      |
| <i>Azadirachta indica</i>       | Leaf       | Aqueous ext.          | 1000 mg/kg soil                  | Azadirachtin               | Akpheokhai <i>et al.</i> 2012 |
| <i>Bauhinia variegata</i>       | Flower     | Aqueous ext.          | 10%                              | Flavonoids, tannins        | Pandey <i>et al.</i> 2001     |
| <i>Brassica campestris</i>      | Flower     | Aqueous ext.          | 10%                              | Glucosinolates             | Pandey <i>et al.</i> 2001     |
| <i>Brassica napus</i>           | Leaf       | Alcoholic ext.        | 500 ppm                          | Glucosinolates             | Katooli <i>et al.</i> 2011    |
| <i>Bridelia micrantha</i>       | Leaf       | Aqueous ext.          | 10, 25, 50%                      | Tannins, flavonoids        | Okeniyi <i>et al.</i> 2014    |
| <i>Caesalpinia pulcherrima</i>  | Flower     | Aqueous ext.          | 10%                              | Flavonoids, saponins       | Pandey <i>et al.</i> 2001     |
| <i>Calotropis procera</i>       | Leaf       | Aqueous ext.          | 10%                              | Cardiac glycosides         | Singh <i>et al.</i> 2001      |
| <i>Carum capticum</i>           | Aerial     | Essential oil         | 1000 µL/L                        | Carvone, limonene          | Gupta <i>et al.</i> 2011      |
| <i>Cassia alata</i>             | Leaf       | Powder                | 5 g/kg soil                      | Anthraquinones, flavonoids | Ugwuoke <i>et al.</i> 2011    |
| <i>Catharanthus roseus</i>      | Leaf       | Aqueous ext.          | 10%                              | Alkaloids                  | Sosamma & Jayasree 2002       |
| <i>Chenopodium ambrosioides</i> | Aerial     | Essential oil         | 6.49 g/mL                        | Ascaridole, p-cymene       | Bai <i>et al.</i> 2011        |

Table 2. Continued (1).

| Plant species                 | Plant part  | Botanical formulation | Concentration   | Major bioactive compounds     | Ref.                          |
|-------------------------------|-------------|-----------------------|-----------------|-------------------------------|-------------------------------|
| <i>Cinnamomum cassia</i>      | Bark        | Ethanollic ext.       | 50–400 µg/mL    | Cinnamaldehyde,               | Khan <i>et al.</i> 2021       |
| <i>Cinnamomum zeylanicum</i>  | Bark        | Essential oil         | 0.1–1 mg/mL     | Cinnamaldehyde, Eugenol       | Fanelli <i>et al.</i> 2025    |
| <i>Citrus medica</i>          | Leaf        | Aqueous ext.          | 10, 25, 50%     | Limonoids                     | Okeniyi <i>et al.</i> 2014    |
| <i>Clerodendrum indicum</i>   | Leaf        | Essential oil         | 100 ppm         | Triterpenoids                 | Joymati Devi 2007             |
| <i>Clerodendrum serratum</i>  | Leaf        | Essential oil         | 10 ppm          | Alkaloids, flavonoids         | Joymati Devi 2007             |
| <i>Couroupita guianensis</i>  | Whole plant | Powder                | 80 ppm          | Alkaloids, saponins           | Pavaraj <i>et al.</i> 2012    |
| <i>Crotalaria juncea</i>      | Leaf        | Aqueous ext.          | 10%             | Alkaloids, flavonoids         | Sosamma & Jayasree 2002       |
| <i>Crotalaria</i> spp.        | Leaf        | Aqueous ext.          | 10%             | Alkaloids, flavonoids         | Sosamma & Jayasree 2002       |
| <i>Cymbopogon citratus</i>    | Leaf        | Ash                   | 3 g/kg soil     | Citral, geraniol              | Ononuju & Kpadobi 2008        |
| <i>Cymbopogon citratus</i>    | Aerial      | Essential oil         | 5–10 mL/L       | Citral, geraniol              | Moreira <i>et al.</i> 2005    |
| <i>Cymbopogon flexuosus</i>   | Aerial      | Essential oil         | 7.47 ppm        | Citral, geraniol              | Archana <i>et al.</i> 2006    |
| <i>Cymbopogon flexuosus</i>   | Aerial      | Essential oil         | 100 ppm         | Citral, geraniol              | Pandey <i>et al.</i> , 2000   |
| <i>Cymbopogon martini</i>     | Aerial      | Essential oil         | 1000 ppm        | Geraniol, citronellol         | Pandey <i>et al.</i> , 2000   |
| <i>Cymbopogon winterianus</i> | Aerial      | Essential oil         | 5–10 mL/L       | Citronellal, geraniol         | Moreira <i>et al.</i> 2005    |
| <i>Cymbopogon winterianus</i> | Leaf        | Methanolic ext.       | 5%              | Citronellal, geraniol         | Gill <i>et al.</i> 2001       |
| <i>Datura metel</i>           | Leaf        | Aqueous ext.          | 1000 mg/kg soil | Tropane alkaloids             | Akpheokhai <i>et al.</i> 2012 |
| <i>Eucalyptus citriodora</i>  | Aerial      | Essential oil         | 250 ppm         | Citronellal, limonene         | Pandey <i>et al.</i> , 2000   |
| <i>Eucalyptus globulus</i>    | Aerial      | Essential oil         | 125–1000 µL/L   | 1,8-cineole, limonene         | Gupta <i>et al.</i> 2011      |
| <i>Eucalyptus meliodora</i>   | Aerial      | Essential oil         | 807 µg/mL       | 1,8-cineole, limonene         | Ntalli <i>et al.</i> 2010     |
| <i>Eucalyptus</i> spp.        | Leaf        | Methanolic ext.       | 5%              | 1,8-cineole                   | Gill <i>et al.</i> 2001       |
| <i>Eucalyptus</i> spp.        | Leaf        | Powder                | 66 ppm          | 1,8-cineole, $\alpha$ -pinene | Ibrahim <i>et al.</i> 2006    |
| <i>Eugenia caryophyllata</i>  | Flower      | Essential oil         | 200 ppm         | Eugenol                       | Sadeghi <i>et al.</i> 2012    |
| <i>Eugenia caryophyllata</i>  | Shoot buds  | Essential oil         | 151%            | Eugenol                       | Meyer <i>et al.</i> 2008      |

Table 2. Continued (2).

| Plant species                     | Plant part     | Botanical formulation | Concentration | Major bioactive compounds    | Ref.                            |
|-----------------------------------|----------------|-----------------------|---------------|------------------------------|---------------------------------|
| <i>Ficus exasperate</i>           | Leaf           | Powder                | 5 g/kg soil   | Flavonoids, triterpenes      | Ugwuoke <i>et al.</i> 2011      |
| <i>Foeniculum vulgare</i>         | Flower buds    | Powder                | 43 ppm        | Anethole, fenchone           | Ibrahim <i>et al.</i> 2006      |
| <i>Foeniculum vulgare</i>         | Aerial         | Essential oil         | 231 µg/mL     | Anethole, fenchone           | Ntalli <i>et al.</i> 2010       |
| <i>Glycosmis pentaphylla</i>      | Leaf           | Aqueous ext.          | 0.5–5%        | Flavonoids, alkaloids        | Bhattacharya <i>et al.</i> 2012 |
| <i>Holarrhena antidysenterica</i> | Bark           | Aqueous ext.          | 0.5–5%        | Alkaloids, tannins           | Bhattacharya <i>et al.</i> 2012 |
| <i>Hunteria umbellate</i>         | Leaf           | Aqueous ext.          | 10, 25, 50%   | Alkaloids                    | Okeniyi <i>et al.</i> 2014      |
| <i>Impatiens parviflora</i>       | Flower         | Aqueous ext.          | 10%           | Phenolics, flavonoids        | Pandey <i>et al.</i> 2001       |
| <i>Jatropha curcas</i>            | Leaf           | Powder                | 5 g/kg soil   | Phorbol esters               | Ugwuoke <i>et al.</i> 2011      |
| <i>Lantana camara</i>             | Leaf           | Aqueous ext.          | 5%            | Terpenoids, flavonoids       | Patel <i>et al.</i> 2004        |
| <i>Lippia alba</i>                | Aerial         | Essential oil         | 5–10 mL/L     | Citral, limonene             | Moreira <i>et al.</i> 2005      |
| <i>Lippia alba</i>                | Aerial         | Essential oil         | 20 µL/mL      | Citral, limonene             | Moreira <i>et al.</i> 2005      |
| <i>Lippia sidoides</i>            | Aerial         | Essential oil         | 5–10 mL/L     | Thymol, carvacrol            | Moreira <i>et al.</i> 2005      |
| <i>Mallotus oppositifolius</i>    | Leaf           | Aqueous ext.          | 10, 25, 50%   | Phenolics                    | Okeniyi <i>et al.</i> 2014      |
| <i>Melia azedarach</i>            | Leaf           | Essential oil         | 10 ppm        | Limonoids, saponins          | Joymati Devi 2007               |
| <i>Melia azedarach</i>            | Leaf           | Aqueous ext..         | 10%           | Limonoids, saponins          | Singh <i>et al.</i> 2001        |
| <i>Melia azedarach</i>            | Leaf           | Alcoholic ext.        | 500 ppm       | Limonoids, saponins          | Katooli <i>et al.</i> 2011      |
| <i>Melissa officinalis</i>        | Aerial         | Essential oil         | 0.156 µL/mL   | Citronellal, rosmarinic acid | Ntalli <i>et al.</i> 2011       |
| <i>Mentha arvensis</i>            | Aerial         | Essential oil         | 250–500 ppm   | Menthol, menthone            | Pandey <i>et al.</i> 2000       |
| <i>Mentha arvensis</i>            | Aerial         | Essential oil         | 125 mL/L      | Menthol, menthone            | Gupta <i>et al.</i> 2011        |
| <i>Mentha canadensis</i>          | Aerial part    | Aqueous ext.          | 139 µg/mL     | Menthol, menthone            | Ji <i>et al.</i> 2016           |
| <i>Mentha microphylla</i>         | Leaf & Flowers | Powder                | 65 ppm        | Menthol, menthone            | Ibrahim <i>et al.</i> 2006      |
| <i>Mentha piperita</i>            | Aerial         | Essential oil         | 250–500 ppm   | Menthol, menthone            | Pandey <i>et al.</i> 2000       |

Table 2. Continued (3).

| Plant species                 | Plant part  | Botanical formulation | Concentration    | Major bioactive compounds  | Ref.                           |
|-------------------------------|-------------|-----------------------|------------------|----------------------------|--------------------------------|
| <i>Mentha pulegium</i>        | Aerial      | Essential oil         | 0.153 $\mu$ L/mL | Pulegone                   | Ntalli <i>et al.</i> 2011      |
| <i>Mentha spicata</i>         | Aerial      | Essential oil         | 250–500 ppm      | Carvone, limonene          | Pandey <i>et al.</i> , 2000    |
| <i>Mentha spicata</i>         | Aerial      | Essential oil         | 0.1–1 mg/mL      | Menthol, Carvone           | Vimala <i>et al.</i> 2025      |
| <i>Mimusops elengi</i>        | Leaf        | Aqueous ext.          | 500 ppm          | Saponins, flavonoids       | Azhagumurugan & Rajan 2013     |
| <i>Moringa oleifera</i>       | Flower      | Aqueous ext.          | 10%              | Glucosinolates, flavonoids | Pandey <i>et al.</i> 2001      |
| <i>Moringa oleifera</i>       | Leaf        | Aqueous ext.          | 1–10 mg/mL       | Glucosinolates, Flavonoids | Azeem <i>et al.</i> 2023       |
| <i>Mussaenda glabra</i>       | Leaf        | Essential oil         | 100 ppm          | Flavonoids                 | Joymati Devi 2007              |
| <i>Nepeta cataria</i>         | Whole plant | Powder                | 50 ppm           | Nepetalactone              | Pavaraj <i>et al.</i> 2012     |
| <i>Newbouldia laevis</i>      | Leaf        | Powder                | 5 g/kg soil      | Iridoids, flavonoids       | Ugwuoke <i>et al.</i> 2011     |
| <i>Nicotiana tabacum</i>      | Leaf        | Powder                | 1.9 mg/mL        | Nicotine, alkaloids        | Djiwanti <i>et al.</i> 2009    |
| <i>Ocimum basilicum</i>       | Aerial      | Essential oil         | 250–500 ppm      | Linalool, eugenol          | Pandey <i>et al.</i> , 2000    |
| <i>Ocimum basilicum</i>       | Leaf        | Essential oil         | 0.02%            | Linalool, eugenol          | Gill <i>et al.</i> 2001        |
| <i>Ocimum basilicum</i>       | Leaf        | Methanolic ext.       | 5%               | Linalool, eugenol          | Gill <i>et al.</i> 2001        |
| <i>Ocimum sanctum</i>         | Leaf        | Methanolic ext.       | 1%               | Eugenol, ursolic acid      | Gill <i>et al.</i> 2001        |
| <i>Ocimum sanctum</i>         | Leaf        | Essential oil         | 0.02%            | Eugenol, ursolic acid      | Gill <i>et al.</i> 2001        |
| <i>Origanum dictamnus</i>     | Aerial      | Essential oil         | 1.72 $\mu$ L/mL  | Carvacrol, thymol          | Ntalli <i>et al.</i> 2011      |
| <i>Origanum syriacum</i>      | Leaf        | Powder                | 50 ppm           | Carvacrol, thymol          | Ibrahim <i>et al.</i> 2006     |
| <i>Origanum vulgare</i>       | Aerial      | Essential oil         | 1.55 $\mu$ L/mL  | Carvacrol, thymol          | Ntalli <i>et al.</i> 2011      |
| <i>Parkia biglobosa</i>       | Leaf        | Powder                | 5 g/kg soil      | Flavonoids, tannins        | Ugwuoke <i>et al.</i> 2011     |
| <i>Pectis apodocephala</i>    | Aerial      | Essential oil         | 500 $\mu$ g/mL   | Monoterpenes               | Albuquerque <i>et al.</i> 2007 |
| <i>Pectis oligocephala</i>    | Aerial      | Essential oil         | 100 $\mu$ g/mL   | Monoterpenes               | Albuquerque <i>et al.</i> 2007 |
| <i>Pelargonium graveolens</i> | Aerial      | Essential oil         | 250–500 ppm      | Geraniol, citronellol      | Pandey <i>et al.</i> , 2000    |
| <i>Pentanema indicum</i>      | Whole plant | Powder                | 80 ppm           | Sesquiterpene lactones     | Pavaraj <i>et al.</i> 2012     |

Table 2. Continued (4).

| Plant species                     | Plant part  | Botanical formulation | Concentration   | Major bioactive compounds | Ref.                          |
|-----------------------------------|-------------|-----------------------|-----------------|---------------------------|-------------------------------|
| <i>Pimpinella anisum</i>          | Aerial      | Essential oil         | 269 µg/mL       | Anethole                  | Ntalli <i>et al.</i> 2010     |
| <i>Pinus pinea</i>                | Leaf        | Powder                | 44 ppm          | Terpenoids, resin acids   | Ibrahim <i>et al.</i> 2006    |
| <i>Piper betle</i>                | Leaf        | Powder                | 3 µg/mL         | Essential oils, chavicol  | Djiwanti <i>et al.</i> 2009   |
| <i>Piper longum</i>               | Fruit       | Essential oil         | 0.05–0.5 mg/mL  | Piperine, β-Caryophyllene | Vimala <i>et al.</i> 2025     |
| <i>Pistacia terebinthus</i>       | Aerial      | Essential oil         | 1116 µg/mL      | Terpenes, phenolics       | Ntalli <i>et al.</i> 2010     |
| <i>Psidium guajava</i>            | Fruit       | Aqueous ext.          | 100 ppm         | Tannins, flavonoids       | Patel <i>et al.</i> 2004      |
| <i>Pueraria phaseoloides</i>      | Leaf        | Aqueous ext.          | 10%             | Isoflavonoids             | Sosamma & Jayasree 2002       |
| <i>Rauvolfia tetraphylla</i>      | All         | Alcoholic ext.        | 2 mg/mL         | Alkaloids                 | Mandal & Nandi 2013           |
| <i>Ricinus communis</i>           | Leaf        | Alcoholic ext.        | 500 ppm         | Ricin, fatty acids        | Katooli <i>et al.</i> 2011    |
| <i>Sinapis alba</i>               | Seed        | Aqueous ext.          | 1–5%            | Glucosinolates            | Zasada <i>et al.</i> 2009     |
| <i>Syzygium aromaticum</i>        | Shoot buds  | Powder                | 3.9 µg/mL       | Eugenol                   | Djiwanti <i>et al.</i> 2009   |
| <i>Tagetes erecta</i>             | Flower      | Aqueous ext.          | 10%             | Thiophenes                | Pandey <i>et al.</i> 2001     |
| <i>Tagetes minuta</i>             | Whole plant | Essential oil         | 4%              | Thiophenes, flavonoids    | Adekunle 2011                 |
| <i>Tagetes patula</i>             | Leaf        | Aqueous ext.          | 4 mg/mL         | Thiophenes                | Buena <i>et al.</i> 2008      |
| <i>Tectona grandis</i>            | Leaf        | Essential oil         | 100 ppm         | Tannins, flavonoids       | Joymati Devi 2007             |
| <i>Tithonia diversifolia</i>      | Leaf        | Aqueous ext.          | 1000 mg/kg soil | Sesquiterpene lactones    | Akpheokhai <i>et al.</i> 2012 |
| <i>Torreya grandis</i>            | Leaf/Stem   | Crude ext.            | 0.5–5 mg/mL     | Polyphenols, Terpenoids   | Feng <i>et al.</i> 2025       |
| <i>Uvaria klaineana</i>           | Leaf        | Ash                   | 3 g/kg soil     | Alkaloids, phenolics      | Ononuju & Kpadobi 2008        |
| <i>Vitex negundo</i>              | Leaf        | Methanolic ext.       | 5%              | Flavonoids, terpenoids    | Gill <i>et al.</i> 2001       |
| <i>Xylosoma longifolia</i>        | Leaf        | Essential oil         | 10 ppm          | Alkaloids, terpenoids     | Joymati Devi 2007             |
| <i>Zanthoxylum zanthoxyloides</i> | Leaf        | Aqueous ext.          | 1000 mg/kg soil | Alkaloids, lignans        | Akpheokhai <i>et al.</i> 2012 |

**Table 3.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Heterodera avenae*.

| Plant species                 | Plant part | Botanical formulation | Concentration | Major bioactive compounds                    | Ref.                             |
|-------------------------------|------------|-----------------------|---------------|----------------------------------------------|----------------------------------|
| <i>Acronychia pedunculata</i> | Flower     | Methanolic ext.       | 300 mg/disc   | Flavonoids, Alkaloids                        | Karunathilaka <i>et al.</i> 2025 |
| <i>Cinnamomum cassia</i>      | Bark       | Ethanollic ext.       | 50–400 µg/mL  | Cinnamaldehyde, Eugenol                      | Khan <i>et al.</i> 2021          |
| <i>Cymbopogon flexuosus</i>   | Shoot tips | Essential oil         | 4000 µg/mL    | Citral, geraniol                             | Sangwan <i>et al.</i> 1985       |
| <i>Cymbopogon martini</i>     | Shoot tips | Essential oil         | 4000 µg/mL    | Geraniol, citronellol                        | Sangwan <i>et al.</i> 1985       |
| <i>Cymbopogon winterianus</i> | Shoot tips | Essential oil         | 4000 µg/mL    | Citronellal, geraniol                        | Sangwan <i>et al.</i> 1985       |
| <i>Hyssopus cuspidatus</i>    | Aerial     | Essential oil         | 0.35 mg/mL    | Monoterpenes (pinocamphone, isopinocamphone) | Faria & Vicente 2021             |
| <i>Kaempferia allid</i>       | Aerial     | Essential oil         | 91.78 µg/mL   | Terpenoids                                   | Li <i>et al.</i> 2017            |
| <i>Kaempferia galanga</i>     | Aerial     | Essential oil         | 0.1 mg/mL     | Terpenoids, phenolics                        | Faria & Vicente 2021             |
| <i>Mentha canadensis</i>      | Aerial     | Essential oil         | 0.4 mg/mL     | Menthol, menthone                            | Faria & Vicente 2021             |
| <i>Mentha canadensis</i>      | Aerial     | Essential oil         | 385.7 µg/mL   | Menthol, menthone                            | Ji <i>et al.</i> 2016            |
| <i>Moringa oleifera</i>       | Leaf       | Aqueous ext.          | 1–10 mg/mL    | Glucosinolates, Flavonoids                   | Azeem <i>et al.</i> 2023         |
| <i>Ocimum basilicum</i>       | Aerial     | Essential oil         | 0.5 mg/mL     | Linalool, eugenol                            | Faria & Vicente 2021             |
| <i>Torreya grandis</i>        | Leaf/Stem  | Crude ext.            | 0.5–5 mg/mL   | Polyphenols, Terpenoids                      | Feng <i>et al.</i> 2025          |
| <i>Valeriana amurensis</i>    | Aerial     | Essential oil         | 0.3 mg/mL     | Valerenic acids, sesquiterpenes              | Faria & Vicente 2021             |
| <i>Valeriana amurensis</i>    | Roots      | Essential oil         | 311.6 µg/mL   | Valerenic acids, sesquiterpenes              | Li <i>et al.</i> 2015            |

**Table 4.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Heterodera schachtii*.

| Plant species              | Plant part  | Botanical formulation | Concentration  | Major bioactive compounds      | Ref.                       |
|----------------------------|-------------|-----------------------|----------------|--------------------------------|----------------------------|
| <i>Centaurea damascena</i> | Aerial      | Methanolic ext.       | 60–1100 µg/mL  | Phenolic compounds, Flavonoids | Jaafreh <i>et al.</i> 2019 |
| <i>Cineraria maritime</i>  | Leaf & root | Aqueous ext.          | 25 g/200 mL    | Phenolics, flavonoids          | Sasanelli & D'Addabbo 1992 |
| <i>Cinnamomum cassia</i>   | Bark        | Ethanollic ext.       | 50–400 µg/mL   | Cinnamaldehyde, Eugenol        | Khan <i>et al.</i> 2021    |
| <i>Moringa oleifera</i>    | Leaf        | Aqueous ext.          | 1–10 mg/mL     | Glucosinolates, Flavonoids     | Azeem <i>et al.</i> 2023   |
| <i>Satureja hortensis</i>  | Aerial      | Aqueous ext.          | 2000–4000 mg/L | Carvacrol, thymol              | Seyed Moradi & Fadaei 2019 |
| <i>Thymus vulgaris</i>     | Aerial      | Aqueous ext.          | 2000–4000 mg/L | Thymol, carvacrol              | Seyed Moradi & Fadaei 2019 |
| <i>Torreya grandis</i>     | Leaf/Stem   | Crude extract         | 0.5–5 mg/mL    | Polyphenols, Terpenoids        | Feng <i>et al.</i> 2025    |

**Table 5.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Heterodera zeae*.

| Plant species               | Plant part | Botanical formulation | Concentration | Major bioactive compounds | Ref.                      |
|-----------------------------|------------|-----------------------|---------------|---------------------------|---------------------------|
| <i>Aloe vera</i>            | Gel        | Aqueous ext.          | 4%            | Anthraquinones,           | Kumhar <i>et al.</i> 2018 |
| <i>Azadirachta indica</i>   | Leaf       | Powder                | 4 g/plant     | Azadirachtin              | Mehta <i>et al.</i> 2015  |
| <i>Azadirachta indica</i>   | Leaf       | Powder                | 5%            | Azadirachtin              | Baheti <i>et al.</i> 2017 |
| <i>Calotropis procera</i>   | Latex      | Aqueous ext.          | 2–4%          | Cardenolides, Alkaloids   | Kumhar <i>et al.</i> 2018 |
| <i>Calotropis procera</i>   | Leaf       | Powder                | 4 g/plant     | Cardiac glycosides,       | Mehta <i>et al.</i> 2015  |
| <i>Ceriops tagal</i>        | Aerial     | Petroleum ether ext.  | Not specified | Lupeol, Triterpenoids     | Ahmad <i>et al.</i> 2022  |
| <i>Eichhornia crassipes</i> | Leaf       | Powder                | 4 g/plant     | Phenolics, tannins        | Mehta <i>et al.</i> 2015  |
| <i>Euphorbia neriifolia</i> | Latex      | Aqueous ext.          | 4%            | Ingenol derivatives       | Kumhar <i>et al.</i> 2018 |
| <i>Jatropha curcas</i>      | Leaf       | Powder                | 10%           | Phorbol esters            | Baheti <i>et al.</i> 2017 |
| <i>Lantana camara</i>       | Leaf       | Powder                | 10%           | Lantadene, triterpenoids  | Baheti <i>et al.</i> 2017 |
| <i>Vetiveria zizanoides</i> | Roots      | Crude ext.            | Not specified | Sesquiterpenes            | Kumhar <i>et al.</i> 2018 |

**Table 6.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Heterodera cajani*.

| Plant species                | Plant part | Botanical formulation | Concentration | Major bioactive compounds  | Ref.                           |
|------------------------------|------------|-----------------------|---------------|----------------------------|--------------------------------|
| <i>Azadirachta indica</i>    | Leaf       | Powder                | 1%            | Azadirachtin               | Singh & Singh 2001             |
| <i>Azadirachta indica</i>    | Leaf       | Powder                | 4%            | Azadirachtin               | Bhardwaj & Trivedi 1999        |
| <i>Azadirachta indica</i>    | Leaf       | Aqueous ext.          | S/30          | Azadirachtin, Nimbin       | Upadhyay <i>et al.</i> 2003    |
| <i>Calotropis procera</i>    | Leaf       | Powder                | 1%            | Cardiac glycosides         | Singh & Singh 2001             |
| <i>Calotropis procera</i>    | Leaf       | Powder                | 5%            | Cardiac glycosides         | Bhardwaj & Trivedi 1999        |
| <i>Ipomoea fistulosa</i>     | Leaf       | Powder                | 1%            | Alkaloids, phenolics       | Singh & Singh 2001             |
| <i>Lantana camara</i>        | Leaf       | Powder                | 5%            | Lantadene, triterpenoids   | Bhardwaj & Trivedi 1999        |
| <i>Lawsonia inermis</i>      | Leaf       | Powder                | 5%            | Lawsonone                  | Bhardwaj & Trivedi 1999        |
| <i>Moringa oleifera</i>      | Leaf       | Powder                | 1%            | Glucosinolates, flavonoids | Singh & Singh 2001             |
| <i>Moringa oleifera</i>      | Leaf       | Aqueous ext.          | Not specified | Glucosinolates, Flavonoids | Kumhar <i>et al.</i> 2018      |
| <i>Nerium indicum</i>        | Leaf       | Powder                | 5%            | Cardiac glycosides         | Bhardwaj & Trivedi 1999        |
| <i>Terminalia arjuna</i>     | Leaf       | Powder                | 1%            | Tannins, flavonoids        | Singh & Singh 2001             |
| <i>Vetiveria zizanioides</i> | Roots      | Crude ext.            | Not specified | Sesquiterpenes             | Abd-Elgawad <i>et al.</i> 2021 |

**Table 7.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Heterodera glycines*.

| Plant species               | Plant part  | Botanical formulation | Concentration | Major bioactive compounds  | Ref.                       |
|-----------------------------|-------------|-----------------------|---------------|----------------------------|----------------------------|
| <i>Abies</i> spp.           | Bark        | Powder                | 4–5%          | Terpenoids, resin acids    | Kokalis <i>et al.</i> 1994 |
| <i>Acacia nilotica</i>      | Gum         | Powder                | 200 g         | Tannins, flavonoids        | Auwal <i>et al.</i> 2014   |
| <i>Azadirachta indica</i>   | Seed kernel | Powder                | 1000 g        | Azadirachtin               | Auwal <i>et al.</i> 2014   |
| <i>Brassica chinensis</i>   | Aerial      | Powder                | 450 g         | Glucosinolates             | Auwal <i>et al.</i> 2014   |
| <i>Camellia oleifera</i>    | Cake        | Ethanol ext.          | 0.02%         | Polyphenols, saponins      | Wen <i>et al.</i> 2019     |
| <i>Ecklonia maxima</i>      | Whole       | Powder                | 2000 g        | Phlorotannin               | Auwal <i>et al.</i> 2014   |
| <i>Paeonia rockii</i>       | Stem        | Ethanol ext.          | 5–12%         | Paeoniflorin, monoterpenes | Wen <i>et al.</i> 2019     |
| <i>Paeonia suffruticosa</i> | Stem        | Ethanol ext.          | 5–12%         | Paeoniflorin, flavonoids   | Wen <i>et al.</i> 2019     |

**Table 8.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Globodera rostochiensis*.

| Plant species                    | Plant part | Botanical formulation | Concentration                  | Major bioactive compounds  | Ref.                                |
|----------------------------------|------------|-----------------------|--------------------------------|----------------------------|-------------------------------------|
| <i>Allium sativum</i>            | Bulb       | Essential oil         | 5 µL/mL                        | Allicin                    | Ibrahim <i>et al.</i> 2017          |
| <i>Azadirachta indica</i>        | Seed       | Essential oil         | 10 µL/mL                       | Azadirachtin               | Ibrahim <i>et al.</i> 2017          |
| <i>Borago officinalis</i>        | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Pyrrolizidine alkaloids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Borago officinalis</i>        | Aerial     | Powder                | 2%                             | Pyrrolizidine alkaloids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Castanea sativa</i>           | Fruit      | Tannin ext.           | 100, 250, 450 g/m <sup>2</sup> | Hydrolyzable tannins       | Maistrello <i>et al.</i> 2010       |
| <i>Eucalyptus globulus</i>       | Leaf       | Essential oil         | 10 µL/mL                       | 1,8-Cineole, terpenoids    | Ibrahim <i>et al.</i> 2017          |
| <i>Eucalyptus globulus</i>       | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | 1,8-Cineole, terpenoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Eucalyptus globulus</i>       | Aerial     | Powder                | 2%                             | 1,8-Cineole, terpenoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Heracleum persicum</i>        | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Furanocoumarins            | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Heracleum persicum</i>        | Aerial     | Powder                | 2%                             | Furanocoumarins            | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Laurus nobilis</i>            | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Eugenol, terpenoids        | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Laurus nobilis</i>            | Aerial     | Powder                | 2%                             | Eugenol, terpenoids        | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Lavandula officinalis</i>     | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Linalool, linalyl acetate  | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Lavandula officinalis</i>     | Aerial     | Powder                | 2%                             | Linalool, linalyl acetate  | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Lepidium sativum</i>          | Aerial     | Aqueous ext.          | 1%                             | Glucosinolates, flavonoids | Fatemy 2018                         |
| <i>Matricaria chamomilla</i>     | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Chamazulene, flavonoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Matricaria chamomilla</i>     | Aerial     | Powder                | 2%                             | Chamazulene, flavonoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Raphanus sativus</i>          | Whole      | Powder                | 20 g/kg soil                   | Glucosinolates             | Ibrahim <i>et al.</i> 2017          |
| <i>Rosa hybrid</i>               | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Polyphenols, flavonoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Rosa hybrida</i>              | Aerial     | Powder                | 2%                             | Polyphenols, flavonoids    | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Salvia officinalis</i>        | Leaf       | Essential oil         | 10 µL/mL                       | Thujone, camphor           | Ibrahim <i>et al.</i> 2017          |
| <i>Tagetes patula</i>            | Whole      | Powder                | 20 g/kg soil                   | Thiophenes, carotenoids    | Ibrahim <i>et al.</i> 2017          |
| <i>Thymbra spicata</i>           | Whole      | Powder                | 20 g/kg soil                   | Thymol, carvacrol          | Ibrahim <i>et al.</i> 2017          |
| <i>Tribulus terrestris</i>       | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Saponins, flavonoids       | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Tribulus terrestris</i>       | Aerial     | Powder                | 2%                             | Saponins, flavonoids       | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Trigonella foenum-graecum</i> | Seed       | Aqueous extract       | 4%                             | Saponins, flavonoids       | Pourmahdi & Fatemi 2013             |
| <i>Viola cornuta</i>             | Aerial     | Aqueous ext.          | 100 g DW/100 mL water          | Flavonoids, phenolics      | Aghazadeh Naeeni <i>et al.</i> 2012 |
| <i>Viola cornuta</i>             | Aerial     | Powder                | 2%                             | Flavonoids, phenolics      | Aghazadeh Naeeni <i>et al.</i> 2012 |

**Table 9.** Nematicidal activity of selected plant species, botanical formulations, and major bioactive compounds against *Globodera pallida*.

| Plant species                  | Plant part | Botanical formulation | Concentration   | Major bioactive compounds | Ref.                             |
|--------------------------------|------------|-----------------------|-----------------|---------------------------|----------------------------------|
| <i>Allium sativum</i>          | Bulb       | Aqueous ext.          | 7840 & 983 µL/L | Allicin                   | Danquah <i>et al.</i> 2013       |
| <i>Brassica juncea</i>         | Seed meal  | Soil amendment        | Not specified   | Glucosinolates            | Bhatta <i>et al.</i> 2023        |
| <i>Solanum sisymbriifolium</i> | Whole      | Trap crop             | Not applicable  | Root exudates             | Gómez-Armesto <i>et al.</i> 2025 |

among nematode species, reflecting both differences in essential oil composition and species-specific susceptibility to individual phytochemicals.

Among these botanical products, essential oils rich in carvacrol and thymol, particularly those obtained from *Thymus* and *Origanum* species, consistently demonstrated potent larvicidal activity. Their lipophilic properties facilitate penetration through the nematode cuticle, disrupting membrane integrity and nervous system function, ultimately leading to paralysis and mortality. Flavonoids and alkaloids, by contrast, appear to impair nematode reproduction and mobility, possibly by modulating key metabolic enzymes and signaling pathways involved in nematode development and reproduction.

The predominance of larvicidal activity over ovicidal activity indicates that most plant-derived metabolites primarily target the infective J2 stage, as reflected by the higher proportion of studies reporting J2 mortality (61%) than egg-hatching inhibition (39%). This pattern is biologically significant because the J2 stage is the only infective and mobile stage responsible for host location, root penetration, and the establishment of feeding sites. Consequently, compounds targeting the infective J2 stage are likely to provide more immediate suppression of nematode infection and crop damage. In contrast, metabolites with predominantly ovicidal activity contribute to long-term population suppression by reducing egg viability and limiting the emergence of infective juveniles.

Although saponins, tannins, and sesquiterpene lactones were reported less frequently than monoterpenes and limonoids, they nevertheless represent valuable classes of natural nematicides owing to their structural diversity and complementary modes of action. Overall, the available evidence identifies monoterpenes and limonoids as the most extensively investigated

phytochemical groups for nematode management, reflecting their broad-spectrum biological activity, chemical diversity, and considerable potential as lead compounds for the development of sustainable botanical nematicides.

#### Plant–nematode specificity

A comparative analysis of plant species and their nematode targets revealed both broad-spectrum and species-specific patterns of activity. *Azadirachta indica* and *Mentha* spp. exhibited activity against both *Meloidogyne* spp. and *Heterodera* spp., suggesting that their chemically diverse secondary metabolites act on conserved physiological targets shared among different groups of plant-parasitic nematodes. In contrast, *Allium sativum* exhibited greater specificity towards *Heterodera* spp., likely owing to its sulfur-containing compounds, particularly allicin and related organosulfur metabolites, which have demonstrated pronounced activity against cyst nematodes. Such specificity is likely influenced by interspecific differences in nematode biology, including cuticle permeability, egg structure, feeding behavior, and detoxification capacity, which collectively determine susceptibility to different classes of phytochemicals. These findings emphasize that the selection of botanical nematicides should be guided by the biology and susceptibility of the target nematode species, thereby improving control efficacy while minimizing unnecessary applications.

#### Functional correlations and synergistic potential

The scatter plot analysis identified distinct clusters of phytochemicals associated with specific modes of action, suggesting that different classes of secondary metabolites may provide complementary mechanisms for nematode suppression. Such clustering patterns highlight the potential for synergistic interactions among selected phytochemicals, although these interactions require experimental validation. For example, the coexistence of

flavonoids and terpenoids in many *Lamiaceae* species may provide multi-target activity by affecting different physiological processes in nematodes, thereby potentially reducing the risk of resistance development.

Consistent with these clustering patterns, azadirachtin and carvacrol were among the phytochemicals most frequently associated with strong nematocidal activity across the reviewed studies. These findings provide a valuable basis for prioritizing candidate compounds in formulation development, optimization of botanical mixtures, and subsequent field validation.

### **Implications for sustainable crop protection and future research priorities**

The findings support the integration of medicinal plants into nematode management programs, particularly in organic and low-input farming systems. Their biodegradability, low toxicity to non-target organisms, and compatibility with soil microbiota make them promising components of sustainable agriculture and integrated pest management (IPM) programs.

Nevertheless, several challenges must be addressed before botanical nematicides can be widely adopted, including the standardization of extract composition and concentration, variability in phytochemical profiles among plant species, chemotypes, and growing conditions, and the development of stable, scalable formulations. Future research should therefore prioritize the optimization of extraction and formulation technologies, well-designed field trials to validate laboratory findings under diverse agroecological conditions, elucidation of synergistic interactions among bioactive compounds, and investigation of the genetic and environmental factors that influence phytochemical production and nematocidal efficacy.

Despite the substantial progress achieved in identifying nematocidal medicinal plants and their bioactive constituents, several important knowledge gaps remain. Most of the available evidence is derived from laboratory and greenhouse experiments, whereas long-term field validation under diverse agroecological conditions remains limited. Furthermore, the molecular

mechanisms underlying the nematocidal activity of many phytochemicals are still incompletely understood, and relatively little is known about their interactions with soil microbial communities, environmental fate and persistence in soil, and potential effects on non-target organisms. Addressing these gaps through multidisciplinary approaches integrating phytochemistry, metabolomics, molecular biology, and formulation science will be essential for translating promising laboratory findings into reliable and commercially viable botanical nematicides. Ultimately, addressing these challenges will be critical for realizing the full potential of botanical nematicides as reliable components of future nematode management strategies.

### **Conclusions**

Medicinal plants represent a rich and diverse source of bioactive compounds with considerable potential for the sustainable management of plant-parasitic nematodes. The evidence synthesized from the current literature demonstrates that phylogenetically distinct plant lineages produce chemically diverse secondary metabolites capable of suppressing nematodes through multiple complementary mechanisms of action. Although important challenges remain in the standardization of botanical products, formulation development, and field validation, continued advances in phytochemistry, molecular biology, and formulation technologies are expected to accelerate the development of reliable botanical nematicides. The strategic integration of these plant-derived products into integrated pest management (IPM) programs offers a promising pathway toward reducing reliance on synthetic nematicides and promoting more resilient and environmentally sustainable agricultural systems. Further interdisciplinary research and successful translation of laboratory discoveries into field applications will be essential to fully realize the potential of botanical nematicides for sustainable crop protection.

### **Conflict of interest**

The authors declare that they have no conflicts of interest.

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