17 Education and Environmental Nematology

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Abstract

Training and education in biomonitoring require a strong understanding of nematode taxonomy, biology and ecology, and therefore considerable background and depth. To achieve effective training, there have been various educational programmes employing diverse approaches, including comprehensive long-term courses, units on biomonitoring within more general nematology programmes, modular courses, and short, intensive courses. Despite these efforts to improve content and delivery, the training opportunities remain geographically fragmented and often lack long-term support. To address these challenges, additional strategies are suggested to integrate environmental nematology into both formal and non-formal education curricula. Many strategies for improving training and education in biomonitoring particularly, and nematology more broadly, require increased funding, meaning that researchers and educators must effectively communicate the ecological significance of nematodes and the potential benefits of biomonitoring.

17.1 Introduction

Nematodes' ubiquity, abundance, diversity, rapid reproduction and involvement in numerous ecological processes make them ideal candidates for biomonitoring and as bioindicators. However, this complex field with diverse traits also complicates training and education in nematology. Current nematology training is predominantly centred on economically important plant parasites and their interactions with plants, with less focus on other facets of the discipline, such as biomonitoring – a situation that is far from ideal (Cortada *et al.*, 2019). Expanding education and training in other areas of nematology is crucial, not only for their intrinsic value but also to facilitate the broader use of nematodes as bioindicators. However, these efforts are currently limited, fragmented and often inconsistently scheduled. This chapter consolidates information on existing

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and potential training initiatives related to biomonitoring with nematodes, while also proposing strategies to overcome the significant challenges faced.

Because there are few specific training courses or degree specializations in biomonitoring using nematodes, a substantial part of the training and education in this field of study is conducted as part of larger or more general nematology training. Training and education in nematology often require a wider approach than only teaching the correct and consistent identification of economically important plant-parasitic nematodes (PPNs) and animal-parasitic nematodes (APNs). It is necessary to interpret the effects of such species in the wider context of other nematodes, viz. free-living nematodes, and organisms in specific substrates. This is because the composition of nematode communities can vary greatly and significantly influence many ecosystem parameters and vice versa. Therefore, nematodes are particularly valuable for biomonitoring due to their high abundance, diversity (especially in non-polluted environments) and short life cycles. However, education and training in free-living nematodes, including biomonitoring, are often incorporated only as a smaller component of training focused on economically important groups like PPNs.

Free-living nematodes numerically dominate most habitats; they constitute overall approximately 73% of the total nematode community in terrestrial soil ecosystems compared to 27% for PPNs (van den Hoogen *et al.*, 2020), with an even larger proportion in marine and freshwater aquatic sediments (Hodda, 2022a). In all types of habitats, free-living nematodes are major components of food webs and perform critical ecological functions such as decomposition, carbon and nutrient cycling, sediment agitation, parasitism and predation on animals, plants and microbes. These are all ecosystem properties of concern in biomonitoring (Lawton *et al.*, 1995; Bloemers *et al.*, 1997; Hodda *et al.*, 1997; Hodda, 2022b). Free-living nematodes are a major component of most schemes for biomonitoring or using nematode indicators for broader ecosystem properties, such as resilience, evolutionary hotspots, and energy and nutrient transfers (Platt *et al.*, 1984; Hodda and Nicholas, 1986; Lambshead, 1986; Austen and McEvoy, 1997; Bongers and Ferris, 1999; Hodda *et al.*, 2009; Balsamo *et al.*, 2012; Traunspurger, 2021). However, free-living nematodes are under-represented in species descriptions, research and education (Neher, 2010; Sikora *et al.*, 2021; Hodda, 2022c). This means that even courses specifically focused on biomonitoring with nematodes require a lot of general nematology background. Therefore, it is desirable to include free-living nematodes from terrestrial, freshwater and marine habitats as part of more popular general nematology training.

With an emphasis on the diversity of nematodes and the broader soil ecosystem, this chapter outlines the basic and specialized methods developed and used for nematode biomonitoring (constituting smaller or elective parts of general nematology courses). These approaches enable the translation of nematode community data into relationships with soil or sediment properties and functions. This is a very active area of more specialized research for which education can greatly assist in interpreting the plethora of new findings. The focus of this chapter is to highlight the extent to which free-living or beneficial nematodes, and the use of nematodes as bioindicators are included in educational materials, academic curricula and courses. Because these topics are often part of broader training or courses, all types of training are considered.

In agronomy and biology education programmes, the field of nematology is often overlooked, in contrast to virology, mycology and entomology. This is a global phenomenon and is unjustified considering their abundances and the significant roles that nematodes play in soils and sediments. Consequently, there are generally very few courses specifically focused on nematology education and training. Nevertheless, there have been several training and educational programmes attempting to rectify the deficiency in all areas of nematology: general, economic parasites and environmental. Online courses and training programmes have been part of this and are also reviewed in this chapter.

Current or recent education and training initiatives in nematology are nevertheless global in scope, and thus reflective of the widespread distribution of our subject, nematodes (Table 17.1).

Table 17.1. Ongoing and completed (online) training courses on free-living nematodes and their use as bioindicators. (Author's own table.)

Institution and main contact persons	Course/identification name	Focus and tools	Target audience	Ongoing?	Source(s)
Europe					
Ghent University (UGent), Belgium: Nematology Research Unit Dr Wim Bert, Inge Dehennin, Dr Ron de Goede	Soil Biodiversity and Nematodes as Bioindicators of Soil Health is a course unit of the International Master of Science in Agro- and Environmental Nematology (IMaNema)	Sampling, extraction, identification of terrestrial nematodes, functional groups, food web analysis and calculation of relevant indices	Postgraduate students	Yes	https://imanema.ugent.be/; https://studiekiezer.ugent.be/international-master-of-science-in-agro-and-environmental-nematology-en; https://studiekiezer.ugent.be/studiefiche/en/C003954/2023 (all accessed 27 August 2025)
	Identification of Aquatic Nematodes	Identification of marine and freshwater nematodes	Anyone interested	In 2018, upon request	https://imanema.ugent.be/aquatic-nema-course/ (accessed 27 August 2025)
Wageningen University and Research (WUR), The Netherlands: Laboratory of Nematology, and Biointeractions and Plant Health Dr Gerard Korthals, Dr S. Brandt	Identification of terrestrial and freshwater nematodes for ecologists/environmentalists	Basic identification skills, sampling, various extraction techniques, functional groups, food web analysis and calculation of relevant indices	Postgraduate students, consultants, extensionists and other interested persons	Yes	https://www.wur.nl/en/research-results/chair-groups/plant-sciences/laboratory-of-nematology/education/course-identification-of-terrestrial-and-freshwater-nematodes-for-ecologists-environmentalists.htm (accessed 27 August 2025)
WUR, The Netherlands: Soil Biology Group Dr Giulia Bongiorno, Dr Ron de Goede, Tamás Salánki	Soil Biology Lab Skills Course for Assessing Soil Functions	Five-day course to define which measurements of soil biology are relevant for which soil functions. The training is hybrid approach including lectures, laboratory and field sessions, of which one day is focused on nematodes	Postgraduate students, consultants, extensionists and other interested persons	Yes	https://biosisplatform.eu/services/training-and-workshops/soil-biology-lab-skills-course-assessing-soil-functions (accessed 27 August 2025)

USA					
University of Vermont: Plant and Soil Science Department Dr Deborah Neher	Soil Ecology	Lectures and hands-on laboratory sessions. Use of simple key to functional groups and computing indices including Maturity Index (MI), Structure Index (SI) and Enrichment Index (EI)	Graduate students	Yes	https://www.uvm.edu/cals/ale/profile/deborah-neher (accessed 10 September 2025)
University of Florida: Entomology and Nematology Dr Dorota Porazinska	Nematode Morphology and Anatomy Nematode Systematics and Molecular Phylogeny	Basic skills in taxonomy, classification, and skills in environmental nematology	Graduate students	Yes	Online: NEM6101, https://entnemdept.ufl.edu/academics/syllabi/NEM_6101_syllabus.pdf (accessed 10 September 2025) In person: NEM6101L, https://entnemdept.ufl.edu/academics/syllabi/NEM6101L.pdf (accessed 10 September 2025) Online: NEM6102, https://entnemdept.ufl.edu/academics/syllabi/NEM_6102.pdf (accessed 10 September 2025). Also ad hoc online nematode metabarcoding
University of California, Davis: College of Agricultural and Environmental Sciences Dr Shahid Siddique	Introduction to Nematology	Relationship of nematodes to the human environment. Classification, morphology, ecology, distribution and importance of nematodes occurring in water and soil as parasites of plants and animals	Undergraduate students	Yes	https://catalog.ucdavis.edu/departments-programs-degrees/entomology-nematology/nematology-minor/#requirementstext (accessed 27 August 2025)
University of California, Riverside: Department of Nematology Prof. Ole Becker	Soil Ecology	Examination of soil biota and relationships with plants and the soil environment. Importance of different groups examined from rhizosphere to ecosystem	Undergraduate students	Yes	https://nematology.ucr.edu/academics/courses (accessed 27 August 2025)
	Biology of Nematodes	Morphology, physiology, development, genetics, behaviour and ecology of nematodes from parasitic and free-living habitats	Undergraduate students	Yes	

Continued

Table 17.1. Continued.

Institution and main contact persons	Course/identification name	Focus and tools	Target audience	Ongoing?	Source(s)
Africa					
Institute of Tropical Nematology (IITA) and International Centre of Insect Physiology and Ecology (ICIPE): NemAfrica team in collaboration with IMaNema, UGent Dr Danny Coyne (IITA, Kenya), Dr Solveig Haukeland (ICIPE, Kenya), Dr Laura Cortada (UGent)	Basic Crash Course in Nematology	Basic identification skills, sampling and various extraction techniques	Now mainly extension officers, but previously undergraduate and postgraduate students, consultants and other interested persons	Yes, since 2018	https://imanema.ugent.be/basic-crash-course-nematology-kenya-bccn/; https://studiekiezer.ugent.be/international-master-of-science-in-agro-and-environmental-nematology-en (both accessed 27 August 2025)
University of the Free State (UFS), South Africa: Natural and Agricultural Sciences Dr Candice Janse van Rensburg (Dr Mieke Daneel and Prof. Gerhard du Preez, North-West University)	Short learning programmes in: Free-living nematode identification for ecologists and taxonomists; and Applied plant nematology	Free-living nematode systematics, trophic group identification, identification of nematode genera and aspects of nematode ecology. Basic identification skills, sampling, extraction techniques. Utilization of nematode-based indices (NBIs) and Nematode Indicator Joint Analysis (NINJA) online tool	Anyone with a secondary qualification as well as graduate and postgraduate students	To be continued at UFS	https://www.ufs.ac.za/kpa/programmes/free-living-nematode-identification-for-ecologists-and-taxonomists; and https://www.ufs.ac.za/kpa/programmes/applied-plant-nematology (both accessed 12 September 2025)
Asia and Oceania					
CSIRO, National Research Collections Australia Dr Mike Hodda, Dr Kerrie Davies (University of Adelaide)	Nematode Identification and Techniques	Basic identification skills, sampling, various extraction techniques, nematode ecology, including trophic groups, indicators and soil health	Diagnosticians, postgraduate students, consultants, extension officers, plant breeders	Yes, approx. biennial since 1999, next course 2025	mike.hodda@csiro.au

Dr Mike Hodda, Dr Dan Huston	Nematode Identification and Techniques	As above plus molecular techniques	Diagnosticians, extension officers, regulators	Yes, periodic since 2011	
Biological Crop Protection Pty Ltd. (private) Dr Graham Stirling	Master classes in nematology, soil biology and soil health at various venues in Australia and New Zealand	Basic identification, pests particularly of turf, soil health, biological control	Technical staff, agricultural consultants	2022, 2023, not ongoing	graham.stirling@biolcrop.com.au
Japan ASEAN Integration Fund Dr Hideaki Iwahori (Ryukoku University, Japan)	Diagnostics of Plant-Parasitic Nematodes	Diagnostics of plant-parasitic nematodes	Agriculture Department staff	2020, under review	
Fudan University, Shanghai, China	Soil Nematology, Taxonomy and Ecology	Terrestrial nematode identification and ecology	Undergraduate students	2016 and 2019	

17.2 Milestones in the Education of Environmental Nematology

Education on the environmental aspects of nematology, especially soil nematology, is recent and formally published information regarding education in environmental nematology before 2006 is scarce (Neher and Darby, 2006). We suspect that education about beneficial terrestrial nematodes began shortly after the discovery of the bacterivorous vinegar eel nematode *Turbatrix aceti* (Müller, 1783) Peters, 1927, by Petrus Borellus in 1656 (Peters, 1927). Other significant milestones linking nematodes to their environment were in marine environments, with the work of Wieser (1953) on feeding types and Gerlach (1953) on the species-salinity curve. In the 1970s, several nematologists expanded on this foundation, exploring various habitats and using nematodes as environmental bioindicators in terrestrial, freshwater and marine systems. For example, *Panagrellus redivivus* has been used as a bioindicator to detect toxin concentrations of any of 400 individual chemicals that affect development, survival and fecundity (Neher, 2001). Another significant milestone was the development of axenic culture techniques for nematodes in the 1950s and 1960s by Ellsworth C. Dougherty. These techniques were later applied to another rhabditid bacterivore, *Caenorhabditis elegans* (Maupas, 1900) Osche, 1952, which ultimately led to it becoming 'one of the best-understood animals in the world' (Riddle *et al.*, 1997). The ability to culture specific lines with no other organisms in totally defined media allowed even more detailed insights into the effects of various chemicals on organisms generally and use as an indicator species for the likely effects of chemicals on other organisms. *C. elegans* became the model organism for assessing the toxicity of chemicals in aqueous media, particularly fresh waters (Höss *et al.*, 2011, 2023). It was the first multicellular animal whose entire genome was mapped and is of high value in molecular and developmental biology, as well as in research for human diseases. Tietjen and Lee (1975) succeeded in the axenic culture of the marine nematode *Pellioditis marina* (Bastian, 1965) Andrássy, 1983, but its use in biomonitoring or toxicity testing has not been as widespread as that of the previously mentioned terrestrial nematodes, perhaps because this species is from a taxonomic group that is otherwise very uncommon in marine habitats and there is considerable cryptic genetic and biological diversity within what is now recognized as a species complex (Moens and Vincx, 1998; Derycke *et al.*, 2012).

In the 1970s, it became popular to use the nematode:copepod ratio for monitoring marine systems conditions at population level (Rafaelli and Mason, 1981; Neher, 2001). These measures were widely used by researchers and professionals but quickly became refined by Warwick (1981) and later replaced by the *k*-dominance curve developed by Lambshead *et al.* (1983). The nematode:copepod ratio proved to be practical for general ecological surveys, particularly for those who could not identify nematodes or copepods and were focused solely on abundances, but it was not without issues (Coull *et al.*, 1981; Hodda and Nicholas, 1986).

17.3 From Research to Education in Environmental Nematology

Efforts to educate students and scientists about using nematodes as bioindicators of ecosystem health were limited and fragmented until awareness grew of the importance and roles of free-living nematodes from the 1970s. In marine ecological studies, considerable attention was given to trophic diversity, particularly using the trophic index in nematodes, and its relationship to environmental parameters, ecosystem functioning and species richness (Heip *et al.*, 1985). The *k*-dominance curve (Lambshead *et al.*, 1983) was also employed as a tool in pollution studies to assess these relationships. Our understanding of environmental relationships of marine nematodes was reviewed recently by Warwick (2019).

During this early period, before the introduction of the Maturity Index (MI) (Bongers, 1990), research in terrestrial environments was mainly focused on nematode abundance and diversity (Yeates, 1970; Freckman, 1988; Wasilewska, 1979, 1995a,b, 1997). For all these methods, training in efficient extraction and basic recognition of nematodes was required and was provided for marine nematodes in general handbooks (e.g. McIntyre, 1971). More advanced training in identification of trophic types or morphospecies (for *k*-dominance curves in marine habitats) had to be learnt on the job from taxonomic texts (e.g. Platt and Warwick, 1983, 1988; Warwick *et al.*, 1998).

In 1987, Gregor Yeates was invited to present a series of eight lectures on resource utilization by nematodes for MSc students at Wageningen University with the aim 'to stimulate thought and to provoke discussion about the relation of nematode populations and ecosystem processes' (Yeates, 1987). Subsequent contributions to research in environmental nematology in terrestrial habitats included: the MI (Bongers 1990), initially focusing only on free-living terrestrial nematodes, but later expanded to other trophic groups and modified (De Goede *et al.*, 1993; Yeates, 1994; Bongers *et al.*, 1995; Korthals *et al.*, 1996; Bongers and Ferris, 1999); and the Enrichment Index (EI) and Structure Index (SI) (Ferris *et al.*, 2001; Ferris, 2010). These discoveries led to intensified educational efforts aimed at expanding the nematode toolset for studying soil ecosystem status. Linking nematodes to ecosystem function and status added relevance necessary to garner interest by policy makers and land managers (Neher, 2010). Significant strides were taken to educate individuals about this specific aspect of nematology, resulting in an enhanced understanding among both scientists and non-scientists.

Following on the contributions mentioned above, Tom Bongers has since 1998 run training sessions for ecologists on the identification of terrestrial and freshwater nematodes at Wageningen University and Research (WUR) (Table 17.1). This immersive 2-week training course is still held annually.

At Ghent University (UGent), a nematology educational programme was established in 1992, including a course on 'Ecology and Population Dynamics of Free-Living Nematodes' (focused on marine nematodes) as part of a 1-year curriculum. By 2003, the programme offered two majors: 'Nematology Applied to Agro-Ecosystems' and 'Nematology Applied to Natural Ecosystems'. When the 2-year Postgraduate International Nematology Course (PINC) launched in 2007, students could also choose the 'Biodiversity/Systematics' track. However, most opted for the 'Agro-Ecosystems' module, receiving limited exposure to beneficial nematodes aside from entomopathogenic nematodes. To address this, since 2018, the succeeding International Master of Science in Agro- and Environmental Nematology (IMaNema) has no longer offered separate modules. Although the programme remains largely agriculture-oriented, nearly all students now take the 6-credit course 'Soil Biodiversity and Nematodes as Bioindicators of Soil Health'.

In 1999, on the other side of the world, Mike Hodda, Kerrie Davies and colleagues from The University of Adelaide began offering training on nematological identification and techniques for students and scientists from Australia, Asia and the Pacific. The intensive 1-week course for up to 15 participants has run biennially since. While initially focused on PPNs, it quickly became clear that there was a need to include free-living nematodes and their relationships with environmental conditions, and other nematodes. Hence, identification of free-living nematodes, allocation to trophic groups, and biomonitoring or soil health were included. The course has been held at various universities in Australia and South-East Asia to reduce travel barriers (Table 17.1). Despite offering university credits, none of the hundreds of participants have used this option.

Other notable examples illustrating the progress of education in nematodes and their use as bioindicators include a workshop at the Second International Congress of Nematology (Veldhoven, The Netherlands, 1990) which produced a resource for soil ecologists to consistently assign nematodes to life-history and trophic groups, respectively (Yeates *et al.*, 1993). The paper represented the best professional agreement about ecological assignments to provide consistency among researchers and studies (Yeates *et al.*, 1993). A recent paper expanded this to include all trophic groups, including vertebrate parasites and marine nematodes (Hodda, 2022b). In 2004, the Society of Nematologists hosted a workshop led by D.A. Neher, T. Bongers and H. Ferris on the 'Computation of nematode community indices'. The workshop's unique approach enables researchers and students to assess soil health by classifying soils using nematodes as bioindicators. Index computations and interpretation were later published as a pair of book chapters (Neher and Darby, 2006, 2009). In 2018, a 2-week identification course on freshwater and marine nematodes was held at

UGent (Belgium), bringing together an international group of 16 participants. The course covered basic nematology techniques, including sampling, taxonomy and ecology, with the first week focused on marine nematodes (N. Smol and T.N. Bezerra) and the second week on freshwater nematodes (A. Zullini).

17.4 Where Are We Now?

As interest has grown in nematodes as bioindicators, soil and sediment ecology, and free-living nematodes, so has the focus on the subject in education. Major progress has been driven by positive developments such as the release of the first edition of this book, the advancement of the United Nation's Sustainable Development Goals (https://sdgs.un.org/goals, accessed 27 August 2025), the Global Soil Biology Initiative (https://www.globalsoilbiodiversity.org/, accessed 27 August 2025), renewed interest in conservation and regeneration agriculture (Kassam *et al.*, 2021), and recognition of the value of diverse soil food webs for food production (http://www.fao.org/conservation-agriculture/en/, accessed 27 August 2025). Assessing negative changes, such as soil degradation in agricultural fields, industrial development areas and natural vegetation, is important too. The exploration and development of new and different bioindicators to monitor the health of terrestrial and aquatic ecosystems have also contributed to the progress and increased interest in nematode biomonitoring. The increased scientific recognition of the diversity, roles and functions of beneficial nematodes (Du Preez *et al.*, 2022) has led to greater public awareness and appreciation. This has also expanded the demand for training to include students and various other stakeholders. Connected with this has been the continuation of intensive, small-group, informal, and in-house training as discussed in the following sections.

17.4.1 Existing nematology education

This section presents a survey of the two main approaches to nematology education:

1. Formal educational programmes.
2. Dedicated, hands-on short courses or non-formal education.

Although most courses are typically conducted face-to-face, some are also offered online in hybrid formats, combining contact and online components (see section on *Dedicated hands-on short courses* below and Table 17.1). However, contact courses with extensive practical work remain the primary and preferred approach. This is particularly relevant when working with free-living nematodes. Despite the development of molecular tools and libraries, visual identification with a microscope is still necessary for identifying most free-living nematodes because few have been sequenced, and sequencing effort lags well behind that of economic nematode groups such as plant parasites.

Formal educational programmes

Accredited, comprehensive nematology education programmes at higher education institutions (HEIs) vary considerably and encompass many topics and concepts apart from bioindicators. As discussed above, these foundational courses necessarily focus on a deeper understanding of the nematode morphology, biology and identification. Consequently, they require experienced nematologists as trainers and much specialized equipment, are limited in availability, and primarily target MSc and PhD levels. Comprehensive coverage of nematode identification, for example, requires experts in many different groups of nematodes, notwithstanding handbooks which cover identification of substantial portions of the phylum (e.g. Goodey, 1963; Andrássy, 1976, 1984; or the more recent Schmidt-Rhaesa, 2013) and the online identification resources listed in Table 17.2.

To the authors' best knowledge, there are no formal, stand-alone courses dedicated to Nematodes as Bioindicators besides those offered at the IMaNema programme from UGent in Belgium and at WUR, The Netherlands. Only at UGent is the Nematodes as Bioindicators course integral to the formal teaching programmes, with a dedicated, 2-year curriculum including lectures and practical sessions. Currently, all students must take a short course on 'Soil biodiversity and nematodes as bioindicators for soil health'. Additionally, there is an option to write a master's thesis on nematode-based indices (NBIs); but from 1999 to 2022, only 6.5% of students accepted this opportunity. The IMaNema programme provides a strong and unique

Table 17.2. Online tools used to understand and analyse data about nematode-based indices (NBIs), faunal analysis, and related parameters to be used as bioindicators of ecosystem health. (Author's own table.)

Inventor/manager and institution	Tool name	Discipline(s)	Focus	Target audience	Source(s)
Howard Ferris (University of California, Davis, USA)	Nemaplex	Nematology	A comprehensive, virtual encyclopaedia about nematodes. Includes a detailed section dedicated to nematodes as environmental indicators. Provides essential information for calculating ecological indices, including NBIs. Forms the starting point for the Nematode Indicator Joint Analysis (NINJA) online tool	Anyone with experience in nematology. Need to have and mastered basic diagnostic and research skills, e.g. nematode counting, picking, identifying. Experience in microscope use	http://nemaplex.ucdavis.edu/Uppermnus/topmnu.htm (accessed 27 August 2025)
Armen C. Tarjan (University of Florida, Lake Alfred) Robert P. Esser (Florida Department of Agriculture, Gainesville) Shih L. Chang (Environmental Protection Agency, Cincinnati, Ohio)	Interactive Diagnostic Key to Plant Parasitic, Free-living and Predaceous Nematodes	Nematology	Exploring the diversity of life on earth as reflected by the nematode world	Students and interested scientists who have a background in nematology	https://nematode.unl.edu/key/nemakey.htm (accessed 27 August 2025)
Bogdan Sieriebriennikov (originally Ghent University, Belgium) Sara Sánchez-Moreno (CSIC/INIA, Spain) Howard Ferris (University of California, Davis, USA) Ron de Goede & Carmen Vazquez-Martin (Wageningen University and Research, The Netherlands)	NINJA: an automated calculation system for nematode-based biological monitoring	Nematology	Development of an R code, compiled in html and deployed across the web, to perform the faunal analysis calculations. NINJA has a user-friendly interface and is freely available. It permits flexibility to override coded default feeding habits of individual nematode taxa. An input table with taxonomic inventory data of nematodes recorded in soil samples only is required. An output is provided within a few seconds indicating a summary of NBI data, faunal analysis, trophic group composition, metabolic footprint data and compost footprint data. There is also a check for correct scientific names. NINJA uses Nemaplex as its database	Nematologists, students and interested scientists (mostly ecologists) with a background in nematology	https://shiny.wur.nl/ninja/ (accessed 27 August 2025)

Continued

Table 17.2. Continued.

Inventor/manager and institution	Tool name	Discipline(s)	Focus	Target audience	Source(s)
Mike Hodda (CSIRO, National Research Collections, Australia)	Universal key to nematode feeding habits	Nematology	Polychotomous and pictorial keys to nematode trophic groups for terrestrial, freshwater and marine habitats, comparison of schemes proposed in the past and for different habitats	Undergraduate and postgraduate students, soil and sediment biologists, researchers	https://www.mapress.com/zt/article/view/zootaxa.5114.1.3 (accessed 27 August 2025)
	Alphabetical list of valid genera and biotope	Nematology	List of valid genera, recently described species, classification and biotope they are found in	Researchers, molecular ecologists	https://www.mapress.com/zt/article/view/zootaxa.5114.1.1 (accessed 25 August 2025)
Deborah Neher (University of Vermont, USA)	Simple key	Soil Biology	Simple key to functional groups that can be used by novices sufficient to compute indices including Maturity Index (MI), Structure Index (SI) and Enrichment Index (EI)	Undergraduate students	Neher (2023)

foundation in nematology and will be operating under a project-based approach until 2027.

In other formal education across universities, nematology courses are presented mostly as stand-alone topics within broader programmes or integrated into other course units such as agriculture, entomology, biology or ecology. Specific elements of NBIs are covered in various contact and online training sessions for soil ecology and/or PPNs at the graduate level at universities and/or at other institutions. Various facets of nematodes as bioindicators of environmental health are currently presented in courses at many universities (in addition to those listed in Table 17.1: University of Michigan, USA; Federal University of Pernambuco, Brazil; Iligan Institute of Technology, Philippines; and University of Western Sydney, Australia). While these programmes may involve formal classes, they often consist of small-group training within laboratory settings for students or guests from other institutes and are frequently associated with research projects.

A detailed survey in 2021 (I. Dehennin, 2021, unpublished results) illustrates the level to which training in nematodes as bioindicators is embedded in university courses. Of 33 HEIs surveyed in sub-Saharan Africa from nine different countries, NBIs were taught at eight out of 33 universities. At the BSc level, 36 course units with a nematology component existed, but only ten included training on nematodes as bioindicators. At the MSc level, only six out of the 35 courses included nematology (Fig. 17.1).

Dedicated hands-on short courses

Specialized nematology courses and workshops have emerged which include a focus on free-living nematodes and their use as environmental indicators. This addresses the lack of formal, accredited nematology programmes and the emphasis on PPNs only. These short courses and workshops offer opportunities to develop specific expertise on this topic but still require substantial background knowledge to understand the complexities of nematodes as environmental indicators. This background may be obtained from courses in general nematology or PPN, or within the short course itself. Training in general or for PPNs and free-living nematodes often intersect, and the crossover between PPNs and free-living nematodes is crucial for mastering nematode morphology, identification and biology.

The diverse statistical approaches to analyse nematode community data are included in many short courses and workshops but can also be found online (e.g. the online NINJA (Nematode

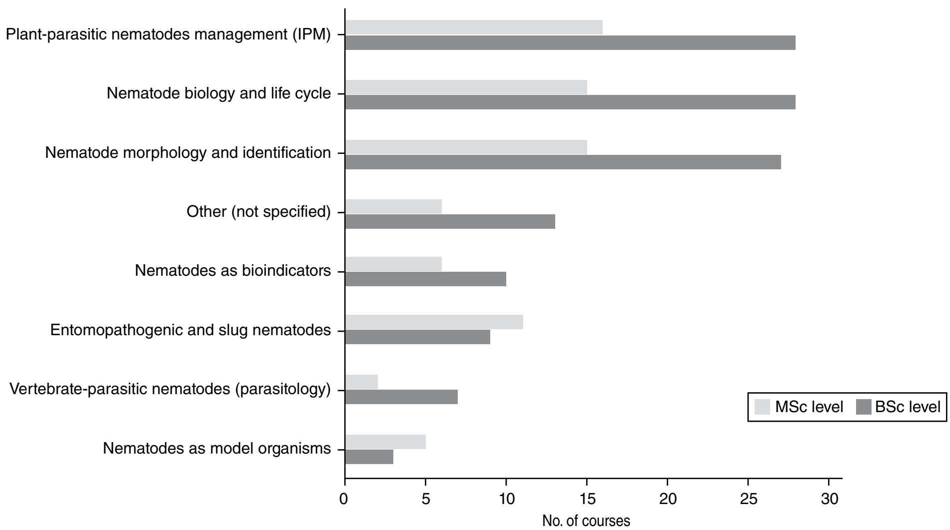

Fig. 17.1. Representation of nematology subjects in existing BSc and MSc programmes in Agriculture/Biology in sub-Saharan Africa. IPM = integrated pest management. (Compiled from I. Dehennin, 2021, unpublished results.) (Author's own image.)

Indicator Joint Analysis) application; https://www.wur.nl/en/product/ninja-nematode-indicator-joint-analysis.htm, accessed 27 August 2025) (Sieriebriennikov *et al.*, 2014). Understanding automatically calculated indices and dealing with raw data from high-throughput, whole-genome or barcode molecular analyses is crucial for accurate interpretation of data.

17.4.2 Online platforms as tools of education

Many online nematology resources, although not necessarily intended as educational resources per se, may still have a role in educating about nematode bioindicators. Online resources can help address the wide geographic dispersion of students, expand access to such students and promote consistency in curricula. Through online platforms, students can access various resources like recorded lectures, interactive tutorials and virtual labs for self-paced learning. These teaching methods are being integrated into some form of formal and informal education (e.g. the course presented at The University of Florida; Table 17.1). Practical experience of fieldwork techniques, microscopy and molecular techniques is still widely regarded as necessary for effectively using nematodes as environmental indicators. These practical skills, however, cannot be taught online.

A potential solution involves combining universally accessible online courses with concise, practical modules tailored for students who have completed online learning. Such hybrid courses can serve as a partial alternative for those with limited ability to engage in hands-on training and can also alleviate financial constraints for organizations and participants in longer formal courses. Examples include the Nematology Digital Learning Platform (Ufora and https://www.youtube.com/@imanemaugent9505, accessed 27 August 2025; UGent, Belgium) for remote practice of nematode identification and analysis, as well as virtual microscopy offering high-resolution images and multifocal video clips from Video Capturing and Editing (De Ley and Bert, 2002). Unfortunately, current initiatives in this area are scattered and focus primarily on PPNs.

There are several online tools available to support and encourage independent learning (Table 17.2). Nemaplex is an online tool and extensive website containing a lot of information, with an emphasis on terrestrial nematodes. It includes recommended colonizer-persister (*c-p*) assignments for the MI (Bongers, 1990), standardized assignments of trophic groups (Yeates *et al.*, 1993), and quantitative tools created by Neher and Darby (2006) and Ferris *et al.* (2001). It has a detailed section specifically dedicated to nematodes as environmental indicators in terrestrial environments. It is widely consulted, regularly updated, and can be used by prospective learners to distinguish terrestrial, free-living nematodes using comprehensive keys. Refinements to faunal analysis and correction of errors led to the creation of an enhanced, easy-to-use, new-generation tool: the Nematode Indicator Joint Analysis (NINJA) by Sieriebriennikov *et al.* (2014) (Table 17.2). This tool can also be employed by students and others to calculate NBIs based on the principles of computing the MI. A prerequisite for using the tool is the identification of free-living nematodes at least to the family level, with genus-level identification being preferable.

A truly comprehensive alphabetical list of all valid nematode genera and their trophic status, along with discussion of the various lines of evidence for trophic relationships, is available online (https://mapress.com/zt/issue/view/zootaxa.5114.1, accessed 12 September 2025). Another very valuable nematode database, Nemys (https://nemys.ugent.be/, accessed 27 August 2025), provides a comprehensive taxonomic overview of all described nematode species. Initially focused on free-living marine nematodes, it has since been expanded to include many terrestrial, freshwater and parasitic nematodes. H. Ferris also maintains a record of the most up-to-date classifications of terrestrial nematodes through the Nemaplex database (http://nemaplex.ucdavis.edu/, accessed 27 August 2025).

17.5 Possible Strategies to Integrate Environmental Nematology into Curricula of Formal and Non-Formal Education

The project ‘Nematology Education in Sub-Sahara Africa (NEMEDUSSA)’ is an example of an initiative addressing the need for training, capacity building and awareness raising in nematology. This was an EU Erasmus+ Capacity Building in

Higher Education project, running from 2021 to 2024, involving 16 partner institutes of which 14 are in sub-Saharan Africa. Although the project primarily focused on general nematology, the consortium developed educational materials for identifying free-living nematodes and their use as bioindicators.

In addition to investing in laboratory equipment for HEIs, staff members from the 14 African partner institutions participated in 'training for trainers' (ToTs) programmes at other partner institutes, including in soil nematology. The training prepared and equipped them to effectively impart their knowledge to students in programmes at their respective institutes. Investing in equipment and staff training transformed some of the partners' nematology laboratories into reference laboratories for research and training. Simultaneously, the partners developed educational material tailored to the African context to support the uptake of nematology in existing BSc and MSc course programmes, including trial runs in the participating universities. Other initiatives of this project raised societal awareness about nematodes through school visits, open houses, student clubs and short courses. A major outcome of this project has been the establishment of the Pan-African Nematology Network (PANEMA) focusing on training that brings together multiple stakeholders, networking and dissemination activities; this PANEMA network organizes monthly webinars and has organized three workshops in Kenya, South Africa and Benin. The project has brought greater attention to nematology in the participating HEIs as a discipline, particularly in the centres where trial runs and PANEMA workshops were conducted.

Since 2011, a long-term project, spanning more than 14 years, has been underway to train an ASEAN (Association of Southeast Asian Nations) Regional Diagnostic Network (ARDN) in nematology. The project is funded by the ASEAN–Australia–New Zealand Free Trade Area's Economic Cooperation Work Programme and the Mekong–Australia Partnership's Vietnam Enhanced Economic Engagement Strategy. The training involves all ten ASEAN countries and is being conducted mainly in ASEAN (Cambodia, Lao PDR, Myanmar, Thailand and Vietnam) as well as in Australia. This programme has benefited from the long-term engagement and is continuing. It is primarily focused on general and plant-parasitic nematology, but also includes components on terrestrial free-living nematodes, soil health and biocontrol. Universities from several ASEAN countries are participating in developing educational and promotional materials, 'train the trainer' sessions and practical fieldwork, with local staff and materials as crucial elements of the programme. The programme has developed and vastly increased the interest in nematology in the region as well as the local capacity and capability in all aspects of nematology.

The two strategic approaches discussed above are both important for developing environmental and biomonitoring nematology as integral parts of both formal and non-formal education and training. Some of the key requirements for these approaches have been the following.

- *Faculty expertise and facilities:* Institutions need well-trained academic and technical staff, along with adequate laboratory equipment, to effectively educate students and others.
- *Syllabus development:* A comprehensive syllabus for nematology training needs to be created to accommodate different education levels. Pre-existing model syllabuses, like the list of topics for an in-depth course on environmental nematode ecology in Table 17.3, can help educators save time and allow students to access course materials easily. Alternatively, modular educational resources, such as those developed for the Australia–ASEAN projects mentioned earlier, can also be considered.
- *Dissemination strategies:* These should target various stakeholders to raise awareness about the importance of educating, researching, and applying knowledge and experience gained in nematology.

Implementing these general strategies may help integrate environmental nematology into other programmes more effectively.

17.6 Challenges and Opportunities in Nematology Education

Nematology education faces several challenges, but strategic attention and innovative solutions are either apparent or available for investigation.

Table 17.3. Suggested topics for inclusion in a comprehensive course on environmental nematology. (Author's own table.)

Topic	Details
Nematode taxonomy	Classification systems, morphological and molecular-based taxonomy, tree of life
Nematode biology	Reproduction, life cycle, locomotion, interaction with biotic and abiotic environment
Nematodes and the soil/sediment food web	Internal food web, predator–prey relationships, parasitism, contribution to soil processes, energy pathways, mitigation of soil-borne diseases
Nematodes as bioindicators	Local soil/sediment quality assessment, biomonitoring, and other soil/sediment health bioindicator systems, trade-offs
Trophic group classification	Trophic groups, classification systems for terrestrial and aquatic species, taxonomic resolution, differences in opinion
Life-history groups	Historical evolution, relationship with the soil/aquatic environment and management
Nematode sampling	Hypothesis formulation, site selection, sampling strategies, corer selection, terrestrial–aquatic soils/sediments. Need for standardization
Nematode extraction	Sample storage, selection extraction method, extraction efficiency. Need for standardization
Nematode identification	Required taxonomic resolution, life stages, dauer larvae
Morphological identification and description	Requires experts in different groups of nematodes, identification literature, knowledge of morphology, morphometrics. Standardized guidelines for species descriptions, including consistency in terminology, measurements and presentation in taxonomic publications (see Mokievsky *et al*., 2024)
Molecular identification	Extraction of DNA, matching methods to goal, primer selection, quantitative PCR (qPCR), Sanger sequencing, metabarcoding, assay standardization, reality check
Image analysis and artificial intelligence	Image databases, data quality and completeness, relationship between traditional taxonomy and computerized image recognition, trait analysis
Quantification and statistical analysis	Categories of diversity (taxonomic, functional, etc.)
Diversity indices/trophic index	Indices, index selection, effective number of species, rarefaction
Maturity indices	Maturity Index (MI), Maturity Index 2-5 (MI2-5), Sigma Maturity Index (ΣMI), colonizer–persister (*c-p*) triangle, trait-based models, non-linearity *c–p*1-5 classification
Pollution indices	*k*-Dominance curve; NemaSPEAR[%]-index (Nematode SPEcies At Risk), sentinel species, empirical models
Trophic group indices	Trophic groups, trophic diversity, Channel Index (CI), bacterivore:fungivore (B/F) ratio
Food web diagnostics	Enrichment Index (EI), Structure Index (SI), interpretation of Nematode Faunal Profile (NFP)
Metabolic footprints	Footprints, graphical interpretation of NFP footprint graph
Multivariate analysis	Principal components analysis (PCA), redundancy analysis (RDA), cluster analyses, network analyses, etc.
Data interpretation and reporting	Hypothesis testing, dissemination and translation of results to the public
Linking MI and food web diagnostics to soil functioning	General ecological theory, soil-based ecosystem services, online nematological analyses tools, Nematode Indicator Joint Analysis (NINJA) online tool, pitfalls in data processing
Reading and understanding an NFP figure	Test hypotheses related to the four quadrats of the NFP figure and functional footprint interpretation
Reading and understanding multivariate analysis figures	How to read biplot and triplot graphs of nematode communities and environmental factors

One of the main challenges is a depleted pool of expert taxonomists: several of the few experts on nematode taxonomy still need to be replaced after retirement, hampering knowledge transfer and jeopardizing the continuity of high-quality education in nematology.

Insufficient and limited financial resources allocated to environmental nematology research and education are also significant barriers to advancing this field, reducing scientific progress and public awareness. This creates a cycle where lack of funding limits progress, and limited progress fails to attract more funding. Persuading policy makers to allocate adequate resources is challenging due to the complexity and low visibility of nematodes.

The limited financial resources are connected to the challenge of attracting students to further their careers by studying free-living nematodes and their use as bioindicators. When opportunities are limited, it can discourage students. The lack of visibility can also be addressed by including NBIs more in curricula at the BSc and MSc levels, which can encourage more students to develop an interest.

In some cases, online tools are fragmented, which makes it difficult for users and policy makers to understand their impact on education. Individual nematologists' efforts also often lack visibility. Global coordination can unite these resources but recognizing contributors and reconciling differing methods and data pose challenges that need resources.

Exploring recent and future technological developments and innovations may assist in addressing the above challenges and training future students and nematologists in environmental nematology. Some approaches like the following may be integrated into both educators' toolkits and curricula.

- *The hybrid flexible or HyFlex teaching method:* This educational method integrates in-person and online learning, adding value and broadening geographic accessibility for educating students in environmental nematology. The availability of every class session and learning activity as a face-to-face session which is also online synchronously and/or asynchronously provides students with the option to choose how they want to participate and learn. It offers fairer opportunities for students with varying physical and emotional dis/abilities to access education.
- *Virtual simulation:* Visual aids such as photographs, figures and illustrations of nematodes and ecosystem processes can greatly enhance knowledge acquisition in environmental nematology. Thus, employing the concept of partial immersion within digital learning environments, such as computers, tablets or phones, could foster a realistic experience.
- *Modern digital microscopy:* Using state-of-the-art cameras and magnified optics, real-time projection of live nematode images offers an excellent opportunity for observation. It makes it easy to capture, save, measure and analyse the images. Observation from computer monitors or projection screens allows multiple people to observe the images simultaneously.
- *Artificial intelligence (AI):* The scientific landscape is currently undergoing a transformation with the integration of AI. In environmental nematology, AI can revolutionize data analysis, such as shown by Brito de Jesus *et al.* (2023) for marine nematodes, automate repetitive tasks and contribute to groundbreaking discoveries that were once inconceivable.
- *Molecular technologies:* Numerous advanced DNA sequencing technologies are becoming more accessible at a rapid pace; for example, new metabarcoding and sequencing methods are being developed to simultaneously identify nematode communities and other microbiota directly extracted from samples. This will require both the development and subsequent training in the analysis and interpretation of the data.
- *Harmonization of online databases and nematode-based indicator tools:* Environmental nematologists have access to a unique set of online resource databases and data analysis tools (Table 17.2). These resources could be pooled and their survival and maintenance guaranteed.

17.7 Conclusions

The role that nematodes can and do play as bioindicators has the potential to increase greatly due to the central position nematodes occupy within food webs, coupled with the global movement towards conserving our natural resources, maintaining healthy ecosystems and ensuring sustainable food production for a fast-growing global population. Nematologists will play a key role in assessing and reporting the status of aquatic and terrestrial ecosystems using nematodes as bioindicators, but this will only occur if nematology education is appropriately valued and managed. This will require effort to ensure that trained scientists, equipped with specialized infrastructure, can in turn train their successors. Education is vital for people to grow, discover and learn, and so the process of education should be continuous.

The ultimate key to all nematology education and training may be convincing governments, education and training managers, and other decision makers to include truly comprehensive nematology training in educational programmes. The review in this chapter has attempted to make the case for this. We, as authors, hope we have demonstrated that it is thoroughly worthwhile to ensure the transfer of knowledge and continuity of nematode bioindicator research and teaching at HEIs and research institutions, as well as to raise awareness among non-scientists about the value of NBIs in contributing to the monitoring and evaluation of ecosystems and environmental health.

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