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Global Research on Plant Nematodes

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Abstract: Background: The more than 4100 species of phytoparasitic nematodes are responsible for an estimated economic loss in the agricultural sector of nearly $125 billion annually. Knowing the main lines of research and concerns about nematodes that affect plants is fundamental. Methods: For this reason, an analysis using bibliometric data has been carried out, with the aim of tracing the state of world research in this field, as well as knowing the main lines of work, their priorities, and their evolution. Results: This will allow us to establish strategic lines for the future development of this research. Conclusions: The analysis has allowed us to detect that the interest in nematodes affecting plants has not stopped growing in the last decades, and that tomato, soybean, and potato crops are the ones that generate the most interest, as well as nematodes of the genus *Meloidogyne* and *Globodera*. Likewise, we have detected that the main lines of research in this field are focused on biological control and host–parasite interaction.

Keywords: nematodes; phytoparasite; bibliometric; *Meloidogyne*; tomato; Scopus

1. Introduction

Nematodes, also called roundworms, are a large group of organisms belonging to the phylum Nematoda [1]. They have adapted to live in many different habitats, which has led to them being the most species-inclusive phylum in the animal kingdom. Nematodes are found in both free-living and parasitic forms of plants and animals [2].

The phytoparasitic nematodes are found in a great diversity of plants and crops throughout the world, causing important economic losses. According to the American Society of Phytopathology (APS), it is estimated that economic losses in the agricultural sector due to nematodes represent 14% of the worldwide crop yield losses, which is almost 125 billion dollars annually [3].

Nematodes are typically bilaterally symmetrical and have a filiform and transparent body without segments, but some plant-parasitic nematodes females acquire a globose shape (e.g., cyst and root-knot females). A common characteristic of all phytoparasitic nematodes is the presence of a stylet, which is located in the stoma or mouth and has a channel through which secretions and food pass. This structure allows phytoparasitic nematodes to pierce the wall of the host cells and inject enzymes that partially digest the cell contents before the nematode sucks it into its digestive system.

According to their life cycle and feeding behavior, phytoparasitic nematodes are classified into three groups:

Endoparasites. They penetrate inside the plant, where all or part of its life cycle takes place. In general, they are very pathogenic because their feeding behavior inside the plant tissues interferes with the absorption of both water and nutrients, causing significant damage to the plants, reducing their growth and productivity [4]. They are mainly root-knot nematodes (*Meloidogyne* spp.), cyst nematodes (*Heterodera* spp., *Globodera* spp.), root-lesion nematodes (*Pratylenchus* spp., *Hirschmanniella* spp., *Radopholus* spp.), stem nematodes (*Ditylenchus* spp.), and the pine wood nematode *Bursaphlenchus xylophilus*.

Ectoparasites. Their life cycle is developed entirely outside the plant, perforating the epidermis or the superficial layers of the host plant's root cortex with the stylet. After feeding, they migrate to another area of the root or another plant. They are mostly found in the soil, although they can also be found in seeds, stems, and the aerial part of the plant (leaves and flowers). Some ectopararasitic nematodes can act as virus vectors, causing important plant diseases (*Xiphinema* spp., *Trichodorus* spp., *Paratrichodorus* spp.)

Semiendoparasites. These can partially penetrate the plant, with one part of the nematode inside the plant and the other part outside, carrying out the egg-laying towards the outside [5], e.g., *Sphaeronema* spp., *Hoplolaimus* spp., and *Helycotylenchus* spp.

Any agricultural crop can be affected by the action of some species of phytoparasitic nematode that reduces the production and quality of crops, causing great economic losses, including staple crops such as cereals, legumes, potatoes, sugar cane, sugar beets, bananas, coconuts, and sweet potatoes, with estimated losses of 10–15% of production. The consequences depend mainly on the population density in the soil and roots, the susceptibility of the cultivated plant species, and the environmental conditions. From an economic point of view, root-knot and cyst nematodes are the most important ones [6]. The effect of nematodes on agriculture is often underestimated as they produce non-specific symptoms that are often confused with situations of water stress, nutritional disorders, soil fertility problems, or with other secondary fungal or bacterial infections that are usually favored by the action of these organisms.

Conventionally, the most used control method against plant-parasitic nematodes has been soil chemical fumigation [7]. However, growing concern about the impact of agrochemicals on public health and the environment has led to the prioritization of other types of control measures. It is now recommended to use integrated control strategies combining different methods so that the environmental impact, as well as the toxicological risk, is minimal, while considering economic feasibility. The design of these strategies will be based on knowledge of the biology of the parasite, the epidemiology of the disease, and the mode of action and effectiveness of the measures to be used.

Agricultural nematology, understood as the science that studies plant-parasitic nematodes, is a relatively young science since the economic impact of these microorganisms on agriculture began to be recognized in the middle of the 20th century. The first works on phytoparasitic nematodes date from the 19th century. From 1850 to 1950, nematological research was mainly focused on taxonomy/systematics and on the discovery of nematodes in different regions of the world. Methodologies were developed to establish the relationship between nematodes and plant pathologies, and from the second half of the 20th century, the number of scientific publications related to laboratory culture, pathologies, or control of nematodes increased considerably [8]. According to Barker [9], some important discoveries boosted the development of nematology in the last century, giving rise to different lines of research. First was the discovery of compounds with nematicidal action. In 1943, D-D (1,3 dichloropropene 1,2-dichloropropane) started to be used as a soil fumigant and became an important prevention tool. For a period, this marked a fundamental line of investigation [10,11], although since the decade of the 1970s, the investigation of new chemical compounds has diminished considerably. The development of nematode-resistant crops was another important tool to assess crop losses and demonstrate the damage caused by phytoparasitic nematodes [12,13]. Finally, numerous researchers focused their studies on the predisposition of plants to certain species of nematodes including their effects on host physiology, sometimes favoring the attack of fungi and bacteria [14]. It was an important step for the research to infect *Arabidopsis thaliana* with two groups of nematodes: cyst nematodes and root-knot nematodes [15]. New molecular methodologies and techniques have enabled nematology to make great progress in recent decades with significant advances in the field of taxonomy and plant–nematode interaction [16,17].

A bibliometric analysis was used to determine trends in authorship and subject matter in nematology during the period from 1969 to 2009 [18], but this work was limited only to the papers published in the Journal of Nematology.

This article aims to develop a methodology based on the bibliometric analysis of published works on phytoparasitic nematodes worldwide. As a result, we hope to be able to draw the state of world research in this field. Knowing what the main lines of work of scientists around the world are, as well as their priorities and their evolution, will allow establishing strategic lines for the future development of these investigations.

2. Materials and Methods

To carry out an exhaustive analysis of the articles published on a scientific theme, the data set can be obtained through a query in the Scopus database. This is the database developed by Elsevier and currently has about 25,000 active journals indexed and almost 200,000 books, from more than 5000 publishers, which means more than 75 million articles, with more than 1 billion references. All these publications range from 1788 to the present day. In addition, Scopus is the database of more than 9.5 million conference proceedings and 16 million author profiles. The other major platform that could be used is the Web of Science (WoS), but it has been published that comparing both databases finds that Elsevier's includes 84% of the WoS titles, while only 54% of the publications included in Scopus are indexed in WoS (Mongeon and Paul-Hus, 2016). The search in a specific database, as in the case of Scopus, is a sample of a size that is statistically sufficiently representative of what is intended to be shown. For this reason, Scopus is the main database consulted in bibliometric analyses and is used in disciplines such as medicine [19] or social sciences [20].

In the present analysis, the query used was [TITLE-ABS-KEY("nemato* AND plant*")]. Note that this was done in April 2020 and that any subsequent search may lead to variations in the results, although the sense of the analysis should not be significantly different. The period analyzed was from 1893 to 2019. 1893 was the first year in which an article on plant nematodes was published [21], and 2019 is the last year for which complete data are available. With the results obtained, the items analyzed are progression of scientific output, publication distribution by countries and institutions, subject area and main authors, and analysis of keywords.

3. Results

3.1. Progression of Scientific Output

The search in the database yielded 17,417 documents. Of these, 95% are written in English, 326 are written in Portuguese, 231 in Chinese, and 138 in Spanish. The rest of the articles are written in other languages, such as German, French, Russian, etc. Note that many US nematologists received their education in Germany and France. Of the 17,417 documents, 14,979 (86%) are articles and 1054 (6%) are reviews. The remaining 8% are conference papers, book chapters, notes, editorials, and others.

Figure 1 shows the evolution of the number of documents on nematodes + plants. Although the first article found in the search dates from 1893, the number of documents published from this year to 1950 is only 36. Therefore, Figure 1 shows the period from 1950 to 2019, the last complete year for which data are available.

Two clearly distinct trends can be seen. The first is from 1950 to 1990. There was a continuous annual growth, and the data can be adjusted to a linear trend line, with an R-squared of 0.923 and a slope of 2.3. The second period begins in 1990 and continues until today, reaching an absolute maximum in 2019 with 1046 articles published. The data for this second trend can be adjusted to another linear trend line, with an R-squared of 0.980 and a slope of 33.5.

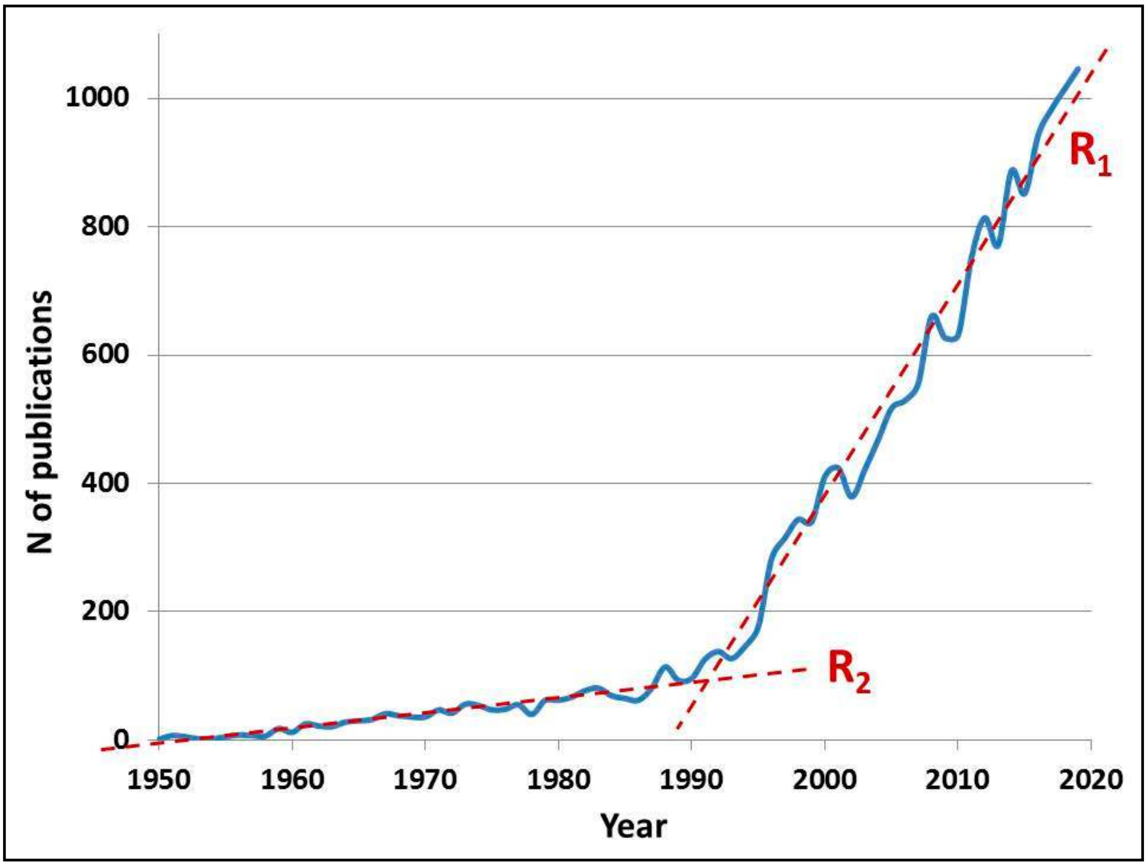

Figure 1. Trend of the number of publications per year on nematodes + plants from the years 1950–2019.

In other words, interest in the subject has grown significantly over the last 30 years. This fact is also confirmed by the number of journals publishing articles on nematodes + plants. Of the 10 journals that have published more than 200 documents in the entire period analyzed, only two of them existed before 1990. These were Annals of Applied Biology and Nematologica (Nematologica fused with Fundamental and Applied Nematology in 1999 to become Nematology). The rest of the journals have emerged in the last 30 years.

3.2. Publication Distribution by Countries and Institutions

In Figure 2, the countries with the most publications on nematodes + plants are represented. Leading the ranking is the United States of America with more than 4500 publications. The remaining countries present between 1672 and 526 publications. These are, in decreasing order: United Kingdom, China, India, Brazil, Germany, France, Australia, Netherlands, Spain, and Belgium. If a ranking attending to the two periods observed in Figure 1 is done, it can be observed that the general ranking is the same as the one obtained in the second period (1991–2019) since it includes 90% of the articles. However, the general ranking is quite different from the one obtained in the first period (1950–1990), in which 10% of the articles were published. In the case of this first period, the United Kingdom headed the ranking, ahead of the United States. In this ranking appear countries that do not appear in the first positions of the general ranking like India or New Zealand.

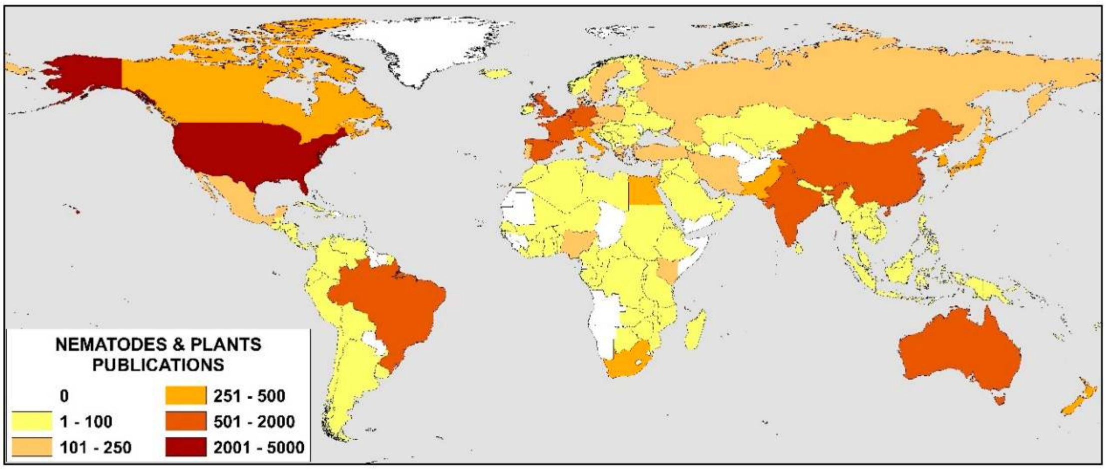

Figure 2. World map of the countries with the highest number of publications in the period 1950–2019.

In Figure 3, the 17 most important institutions in this area are represented, all of them publishing at least 200 articles. Leading the ranking is the USDA Agricultural Research Service, USA. The second position is held by the Wageningen University and Research Centre, the Netherlands. The next five positions are held by American or British institutions. The remaining seven institutions that have published at least 200 articles on nematodes + plants are from Belgium, China, Italy, France, Spain, Brazil, and India.

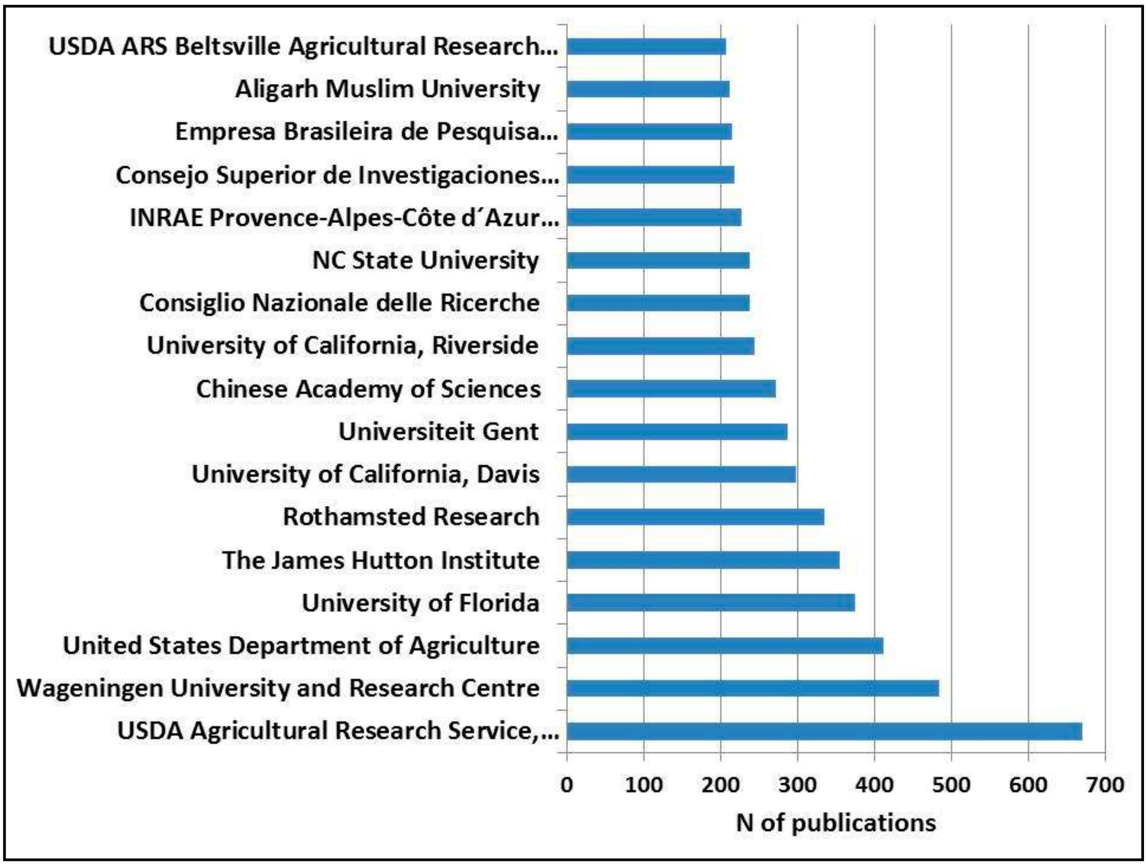

Figure 3. Main institutions related to scientific production on nematodes + plants.

3.3. Subject Area and Main Authors

Figure 4 represents the subject area in which nematode and plant documents are published. Over half of these are related to the area of Agricultural and Biological Sciences, as might be expected. The other half are published in areas related, directly or indirectly, to human or animal health. These are, for example, Immunology and Microbiology, Pharmacology, Toxicology and Pharmaceutics, or Veterinary.

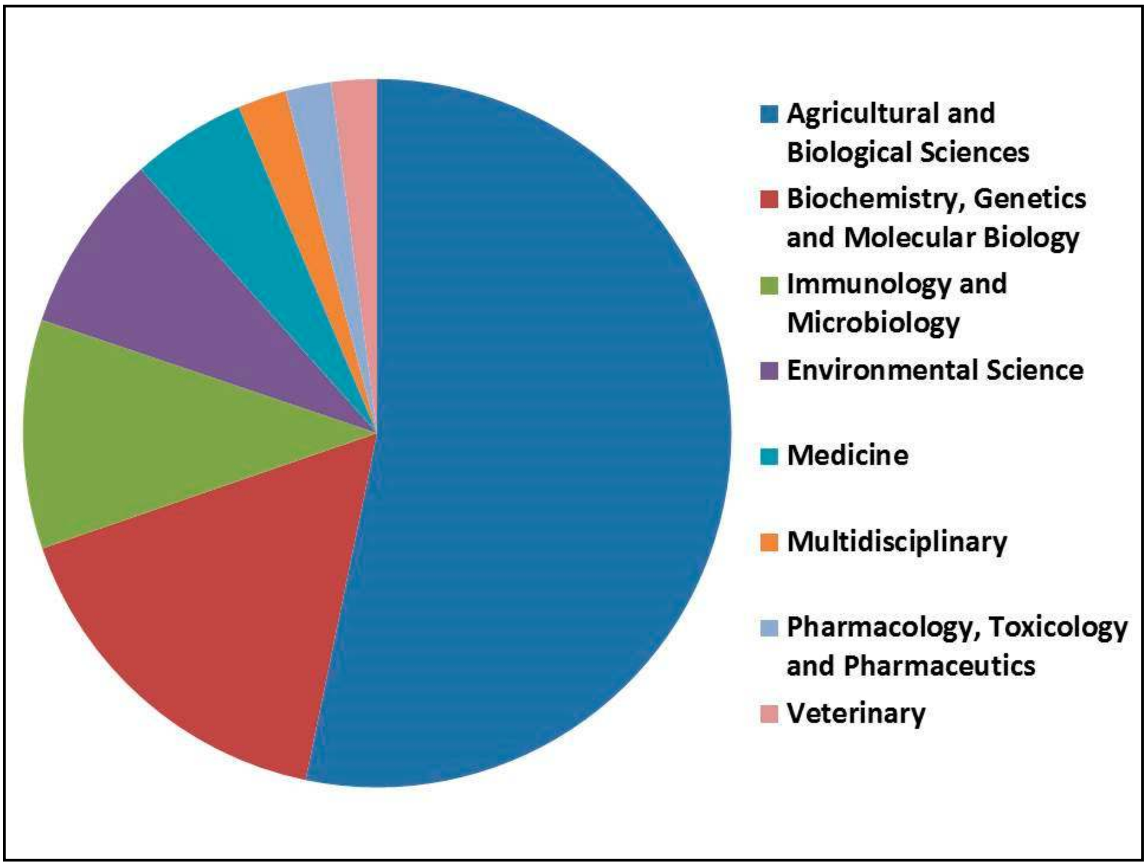

Figure 4. Subject area in which articles on nematodes + plants are published.

The 13 authors with at least 70 articles on nematodes + plants are represented in Table 1. These authors present an average of 88 articles, between 1968 and 2020, which, on average, represent 62.5% of the total scientific production of these authors. This means that most of them have focused their research career on this topic. For only two of them, G. W. Yeates and M. Moens, the number of articles published on this subject represents less than 50% of the total published. On average, these authors have an h-index of 38 and have scientific careers of more than 30 years, with most of the articles published from 1991 onwards. Only G. W. Yeates has a significant number of articles (14) published before this year. Of the 13 authors, only four of them belong to one of the institutions mentioned in the previous section (Figure 3). These are G. Gheysen to the Universiteit Gent, P. Abad to the Université Côte d'Azur, P. Castillo to the CSIC –Consejo Superior de Investigaciones Científicas, (Spain), and E. L. Davis to the North Carolina State University.

There are almost no significant scientific collaborations between these 13 authors. In other words, most of them work along independent lines with no common ground with the work of their more notable colleagues in the field of nematodes + plants. Only the three US authors in Table 1, T. J. Baum, E. L. Davis, and R. S. Hussey, have collaborated in the publication of some 40 papers, focusing on the susceptibility of the plant Arabidopsis to nematodes of the genus Heterodera.

Table 1. Main authors working on publications on nematodes + plants.

Author	Scopus ID	N	P	N %	H	Starting Year	Institution	Country
D. De Waele	7004634773	107	163	65.6	21	1981	Kat. Univ. Leuven	Belgium
G. Gheysen	7003668326	101	189	53.4	48	1988	Univ. Gent	Belgium
T.J. Baum	7102086825	92	113	81.4	48	1996	Iowa State Univ.	USA
P. Abad	55344098800	89	128	69.5	46	1989	Univ. Côte d'Azur	France
P. Castillo	55649239000	88	144	61.1	27	1987	CSIC-IAS	Spain
R.A. Sikora	55964213600	86	150	57.3	34	1982	Univ. Bonn	Germany
R.S. Hussey	7005978336	79	106	74.5	47	1989	Univ. Georgia	USA
G.R. Stirling	7005445587	76	109	69.7	27	1976	Biol. Crop Prot.	Australia
G.W. Yeates	7004404288	74	209	35.4	52	1968	Landcare Research	New Zealand
E.L. Davis	7402374179	73	88	83.0	40	1987	NC St. Univ.	USA
M. Moens	7005471644	73	196	37.2	38	1992	ILVO	Australia
H.J. Atkinson	7101883677	70	126	55.6	36	1973	Univ. Leeds	UK
F.M.W. Grundler	6701683832	70	102	68.6	30	1991	Univ. Bonn	Germany

N: Number of articles published on nematodes + plants; P: number of total articles indexed in Scopus; N %: 100 x; N/P; H: H-index; Year: year of the first publication in the subject.

3.4. Analysis of Keywords

The 160 most abundant keywords in nematode and plant publications were analyzed. All of them appear between 231 and 6465 times. Within these keywords, the six crops that receive the most attention in these publications appear. These are tomato, soybean, potato, Arabidopsis, corn, and wheat. It is known that *Arabidopsis thaliana* is not a plant crop, but it is used in many different types of research subjects, including research subjects related to plant-parasitic nematodes. All of them were analyzed according to the country in which the works in which they appear were published, and the results are shown in Figure 5.

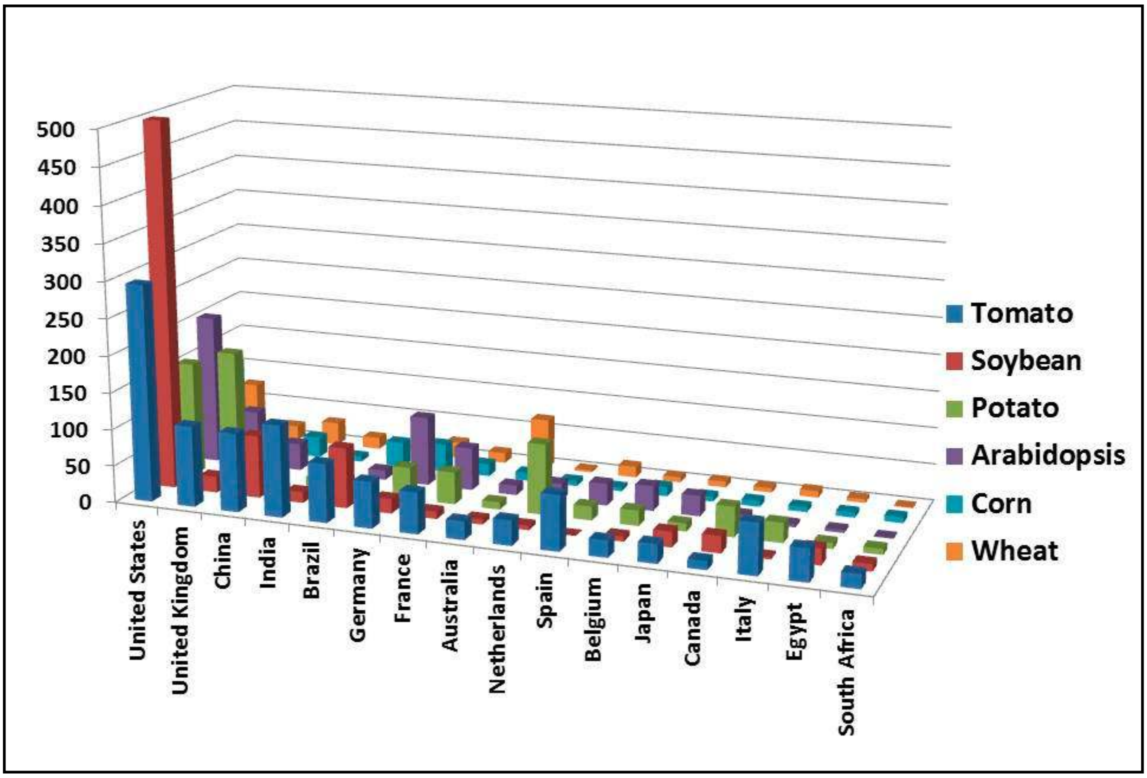

Figure 5. Relationship between crops and the countries with the highest scientific production of nematodes + plants.

Tomato (*Solanum lycopersicum*) receive the most attention in their relationship with nematodes. In fact, this is the case in 6 of the 16 countries that publish the most on this subject: China, India, Spain, Italy, Egypt, and South Africa. The second most important crop was soybean (*Glycine max*). However, this crop receives a lot of attention in the USA, with more than 500 publications on this crop. This means that 2 out of 3 papers published worldwide on soybean and nematodes involve American authors and institutions, which gives an idea of the importance of this crop in the country. Brazil is the second country where the relative weight of publications on soybean and nematodes is greater than that of other crops. USA and Brazil are the two leading countries in the world production of soybean, a crop that every year is gaining more relevance, worldwide, in economic and food terms since it is an excellent source of protein.

Studies of potato (*Solanum tuberosum*) and their relationship to nematodes are the most important in the United Kingdom, the Netherlands, and Canada, while studies of *Arabidopsis thaliana* are the most important in Germany, France, Belgium, and Japan.

Wheat (*Triticum aestivum*) is the fifth most important crop and the one on which most research has been published on nematodes in Australia. More than 20% of articles on wheat and nematodes have been published by Australian authors or institutions. The importance of this crop in Australia is due to the fact that wheat is grown on more than half of the country's farmland and is a key export product, with Australia becoming the fourth largest exporter of wheat, with more than 10 million tonnes by 2019.

On the other hand, these six crops were also studied in relation to the nematode that appears most often in these publications (Figure 6) according to keyword analysis. The two most prominent species are *Meloidogyne javanica* and *Meloidogyne incognita*, which appear in more than 1900 articles each. Most of these articles deal with tomato crops. The nematodes of the family *Meloidogynidae* are the ones that mainly affect this crop, inducing galls in the roots, affecting its functionality by altering water absorption and nutrient transport. A third species in this family is *Meloidogyne hapla*, and although it appears among the seven species with the greatest presence, its relative importance is not as high as that of the two previous species. The next species to appear is *Heterodera glycines*, a nematode that mainly affects soybeans. The next two species are *Globodera rostochiensis* and *Globodera pallida*, which are nematodes that mainly affect potato crops. The last species of nematode to appear is *Heterodera schachtii*. It is mainly associated with sugarbeet and *Arabidopsis thaliana*. This is because this system *Heterodera schachtii*/*Arabidopsis thaliana* has become a powerful and versatile research model to study and characterize the possible interactions between the cyst nematodes and the plants they affect [22]. In addition to these, there are two other species of nematodes that are not of such notable general importance but that affect specific crops, and many studies have been published on them. These are *Bursaphelenchus xylophilus*, which mainly affects pine plantations, and *Radopholus similis*, which affects banana plantations. There are 164 and 133 publications on these, respectively. Only the most frequently cited nematodes appear in this list; other nematodes do not appear, although they affect such important crops as orange trees [23], which are of great economic and agronomic interest.

Finally, the trend of the number of publications per year of the main lines of research was analyzed through the 160 keywords (Figure 7). The lines of research and their associated keywords, in brackets, are plant resistance (resistance, disease resistance, transgenic plant, and RNA interference), nematode virulence (virulence), phylogeny and taxonomy (classification, taxonomy, phylogen, and morphology), soil biodiversity (biodiversity, community structure, soil fauna, species diversity, ecology, and abundance), bioindicators (community structure), integrated pest management or IPM (pest control), biological control (biological control, biological pest control, anthelmintic agent, antinematodal agent, and biocontrol), nematicides (anthelmintic activity, anthelmintics, anthelmintic agent, antinematodal agent, and nematicide), biopesticides (anthelmintic activity, anthelmintics, anthelmintic agent, antinematodal agent, plant extract, and medicinal plant), and host–parasite interaction (host parasite interaction, host parasite interactions, parasitism, host-parasite interaction, gene expression, gene expression regulation).

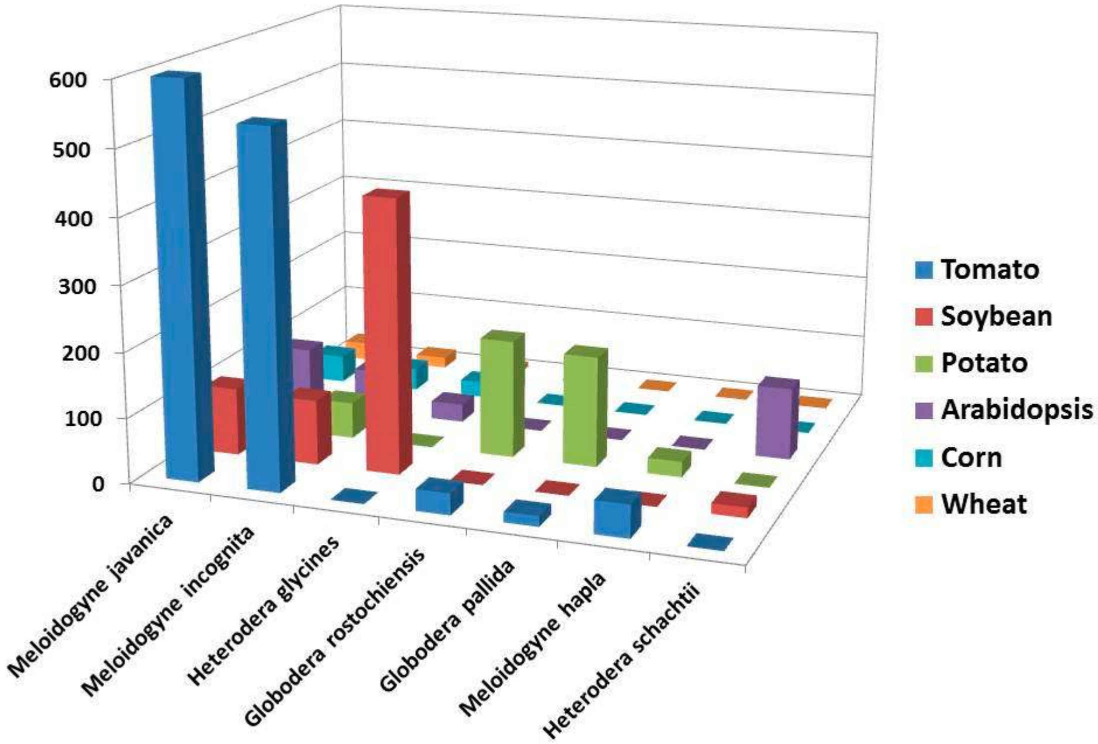

Figure 6. Relationship between the main types of crops and the species of nematodes more present in scientific literature according the keywords.

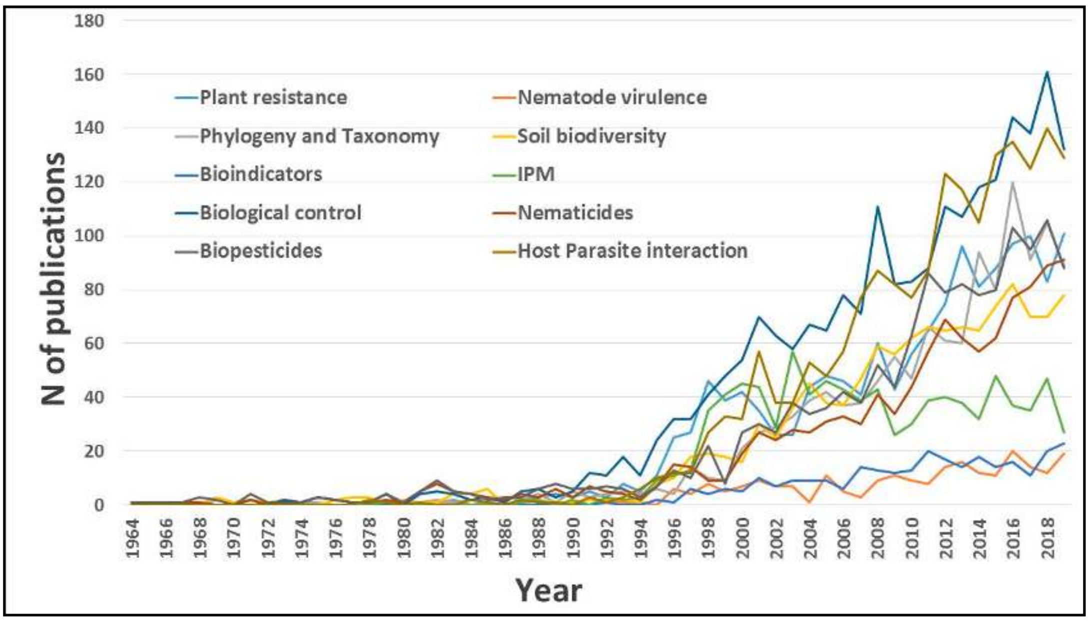

Figure 7. Trend of the main research lines on nematodes + plants through the 160 keywords.

As can be observed, the different research lines can be grouped into research lines with high scientific production (biological control and host-parasite interaction), research lines with medium scientific production (plant resistance, phylogeny and taxonomy, soil biodiversity, nematicides, and biopesticides), and research lines with low scientific production (IPM, bioindicators, and nematode virulence).

Most of this scientific production has taken place since 2010, and it is precisely in the 2010–2019 period that the lines of research on biological control, focused on the alternative that this methodology represents to chemical nematicides and other conventional control methods, and host–parasite interaction, focused on the relationship between the parasite and the plant, have been of greater interest. Other research lines have proved to be more interesting in different periods but are not so at present. For example, this is the case of the studies on IPM, which focused the attention of the scientific community at the end of the 20th century, or the lines of research focused on nematicides or biopesticides, which presented their greatest interest at the end of the 1980s.

4. Discussion

Knowing the fundamental lines of research and concerns about nematodes that affect the main agricultural plantations in the world is fundamental in the development of agricultural policies and in the identification of strategic lines. The decline in production caused by phytoparasitic nematodes can be as much as 15%. For this reason, it is essential to outline the scenario in which world research in this area is being carried out to understand the most pressing concerns of the sector. Some bibliometric analyses have been performed in the past, such as that of R. McSorley in 2011 [18], although this was limited to papers published in the Journal of Nematology between 1969–2009. However, some of the conclusions drawn from that study pointed in a direction that is confirmed in this study, such as the relevant role of the USDA Agricultural Research Service, or the importance that trends in studies related to biological control or resistance were beginning to acquire.

As the evolution in Scientific Output shows, the interest in nematodes affecting plants has not stopped growing, especially in the last thirty years. Tomato, soybean, and potato crops are the most interesting, and nematodes that affect them, *Meloidogyne javanica*, *Heterodera glycines*, or *Globodera rostochiensis*, are the focus of most research articles. In recent years, agricultural production has become a fundamental strategic line of development due to its great economic and food importance at the global level, providing human food, oils, animal feed, and inputs for aquaculture.

For this reason, the countries with the greatest scientific production of nematodes + plants are not only the main producers of these but also the leading economic powers in the world. Thus, among the countries that publish most in this field, the United States stands out, followed by the United Kingdom and China, whose main institutions such as the USDA Agricultural Research Service or the University of Florida focus a good part of their development and investments on the control of infections by phytoparasitic nematodes.

Despite the obvious benefits of this type of analysis, it is impossible to guess where the research direction will lead in the field of phytoparasitic nematodes. In any case, what is clear is that the possibilities offered by this change in research are unlimited in view of the advances in the technologies used and the new challenges it faces. Some of the greatest challenges that humanity will have to face in the future are related to nematodes. These include scarce water resources, pest control, intensive agriculture, and crop diseases. However, to advance knowledge, the application of new technologies in processes such as rapid diagnosis of nematodes or in situ identification of species will be fundamental. On the other hand, the strategies developed by phytoparasitic nematodes throughout evolution such as the exhaustive control of their metabolic activity or the efficient use of water can shed light on issues raised in other species. To this end, molecular and biochemical knowledge of nematodes is of great importance.

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