INTRODUCTION

The word nematodes or nemas (Greek *nema*, *nematos* = thread, oides = resembling) is derived from the Greek root nema. The terms nema and nematology were introduced by Cobb (1932). Chitwood (1957) supported by Cobb, arguing that zoologically speaking, the vernacular word nematode was a corruption of the ordinal name Nematoidea of Rudolphi (1808) which was in use in Germany as the plural equivalent to "Nematoden". Von Siebold (1848) used the ordinal word "Nematodes" which was modified by Diesing (1861), as order Nematoda. Maggenti (1981, 1982) and Goodey (1963) used the names Nemata and Nematodea for Phylum and Class respectively, instead of Nematoda, but the word nematode is more commonly used than nema. According to Ayoub (1980), a word NEMATOID was coined which after modification has become NEMATODE. The nematodes can be defined as multicellular, non-segmented, usually vermiform animals showing a basic bilateral symmetry and possess a pseudocoel – a body cavity lined with an epithelial mesentry. The plant parasitic nematodes are generally called eelworms, phytonematodes, phytohelminths or simply plant nematodes. They parasitize both animals and plants.

Nematodes are widespread in distribution and found in soil, fresh water and salt water wherever organic matter exists, from oceans to mountains, from arctics to tropics and are said to be 'Ubiquitous' (Thorne, 1961). The parasitic forms are important in the health of human being and animals and in the

efficiency of agriculture. The free living forms are known to be present in enormous number in soil and fresh water and undoubtedly have major roles in maintaining the natural ecological balance. The role of the marine forms is almost entirely unexplored. Rarely any crop is free from the attack. They are so numerous that Cobb (1914) aptly remarked "... if all the matter in the universe except the nematodes were swept away, our world would still be dimly recognizable .... we would find it in mountains, hills, valleys, rivers, lakes and oceans represented by a film of nematodes. Out of total known species of nematodes, about 50% are marine, 25% free living, 10% plant parasitic and 15% animal parasitic forms (Ayoub, 1980). Plant parasitic and free living forms are grouped as soil and fresh water nematodes.

BRIEF HISTORY OF NEMATODES

Historical records show that nematode parasites of animals were known to ancient people and were mentioned in early 4500 B.C. The Eber Papyrus and early Egyptian medical records dated 1553-1550 B.C., noted the existence of the large intestinal round worm which was later named as *Ascaris lumbricoides* by Linnaeus. Hippocrates (430 B.C.) was the first to record the pin worm, *Enterobius vermicularis*. In the third century B.C., the Greek philosopher Aristotle (384-322 B.C.) also known as Father of Zoology repeatedly mentioned animal-parasitic nematodes in his writings. Roman Pliny (23-79 AD) mentioned the Guinea worm which was later described as *Dracunculus medinensis*. This dreaded worm grows two to three feet long and lives in the

arms and legs of man, causing excruciating pain. This Guinea worm also had been described in early Egyptian writings. It is believed that the 'fiery serpents' which attacked the Israelitis, as mentioned in the Bible (The Old .... Numbers 21: 6-9) were actually the Guinea worms. The early awareness about the animal parasitic nematodes was partly because of their large size. The invention of compound microscope during the early 17th century, however. helped tremendously in later biological studies. Thus Borellus (1656) observed first free living nematode, *Tubetrix aceti* known as the '"Vinegar eel" using compound microscope.

J. Turbevill Needham, a catholic priest of England in 1743 discovered the first plant parasitic nematode, the wheat gall nematode, *Anguina tritici*, the causal organism of the ear cockle disease of wheat, while examining a portion of shrunken, blackened seed gall in a drop of water under his primitive microscope. He is known as "Father of Nematology". Needham wrote to the president of the Royal Society, London stating that small black grains of smutty wheat had soft fibrous substances which upon soaking in water, took life and yielded a large number of motile worms. He described what he saw in these words:

Upon opening lately the small black grains of smutty wheat they here distinguish from blighted Corn, the latter affording nothing but a black Dust, into which the whole Substance of the Ear is converted, I perceived a soft white fibrous Substance, a small Portion of which I placed upon my Object plate : It seemed to consist wholly of longitudinal Fibres bundled together; and you will be surprised, perhaps that I should say, without any least Sign of Life or Motion. I dropped a Globule of water upon it, in order to try if the Parts, when

separated, might be viewed more conveniently; when to my great Surprise these imaginary Fibres, as it were, separated from each other, took life, moved irregularly, not with a progressive, but twisting Motion, and continued to do so for the Space of Nine or Ten Hours, when I threw them away. I am satisfied that they are a Species of Aquatic Animals, and may be denominated Worms. Eels or Serpents, which they very much resemble.

In recognition to his studies, J.T. Needham, at the age of only thirty four years, was elected Fellow of the Royal Society in 1747. After Needham, Linnaeus (1767), Scopoli (1777), Steinbuch (1799) and others recorded the same species and observed that it also attacked other cereals. M.J. Berkeley (1855) the Father of British mycology, observed "Vibrios" the root-knot nematode, *Meloidogyne* spp. on roots of cucumber plants grown in the green house in England.

No additional observations of plant parasitic nematodes were recorded until Kühn (1857) found *Anguillula dipsaci* = *Ditylenchus dipsaci*, infesting heads of teasel, *Dipsacus fullonum* L.

The crop loss assessment of sugarbeet due to plant parasitic nematodes was realized for the first time by Schacht (1859). He discovered the association of a nematode to the serious decline in the production of sugarbeet (Rübenmudigkeit) in Germany during mid 19th century. The nematode was later named as *Heterodera schachtii* (the sugarbeet cyst nematode) by Schmidt (1871). This serious pest of sugarbeet in Central Europe triggered scientists of that period to study the effectiveness of various control practices, including the application of chemicals such as carbon disulfide. In the second half of the

nineteenth century several important developments held in the field of nematology in European countries, for instance, Bastian (1866) wrote "Monograph of the Anguillulidae" which in the word of Thorne (1961) marked the beginning of the science of nematology. Greeff (1872) noted *Ditylenchus radicicola* producing root galls in *Poa annua* and other grasses. Otto Butschli (1873) gave the first detailed description of the morphology of free living nematodes and pointed out many of the characters which are used today in distinguishing genera and species. He was credited by Thorne (1961) for founding the science of nematology. Cornu (1879) described *Meloidogyne marioni* producing root galls in *Onobrychis sativa.* De Man (1884) wrote a classical taxonomic monograph "Die einheinschen brei in der reinen Erde und in Sussen-Wasser Labenden Nematoden der Niederland ischen Fauna". Goeldi (1887) described *Meloidogyne exigua* from Brazil causing galls on the roots of coffee. Strubell (1888) presented a detailed morphological study of *Heterodera schachtii.* It was so complete that little has been added to it. This fine piece of work was Strubell's only contribution to nematology. Ritzema-Bos (1891) discovered the foliar nematode, *Aphelenchoides fragariae* on strawberry plants.

Many outstanding discoveries in nematology attracted many talented nematologists of the twentieth century. Micoletzky (1922) compiled literature on soil and fresh water nematodes and produced "Die freilenbenden Erd-Nematoden". 1. N. Filipjev (1934) produced an important book on systematics in Russian, "Nematodes-Harmful and beneficial to Agriculture". The English

translation of this work was later published entitled, "A Manual of Agricultural Helminthology (Filipjev & Schuurmans-Stekhoven Jr, 1941). Tom Goodey in 1922 published his first research paper on nematodes. He wrote a book, "Plant Parasitic Nematodes and the Disease they Cause" in year 1933 and in 1951 "Soil and Fresh water Nematodes". He was honoured with the order of the British Empire. Chitwood & Chitwood (1937) wrote a book "An Introduction to Nematology". Carter (1943) reported nematicidal property of Dichloropropane-Dichloropropene (DD). It was a beginning of the era of soil fumigation. Cannon (1941) discovered potato root eelworm (Golden cyst nematode), *Heterodera rostochiensis* (*Globodera rostochiensis*) in the important potato producing region on Long Island, New York. The key discovery of Christie & Albin (1944) was the characterization of "races" or "Physiological Strains" of the root-knot nematode, at a time when all root-knot nematodes were considered to compromise a single species within the genus *Heterodera* viz., *H. marioni*. This investigation resulted in Chitwood's assigning the root-knot nematodes to the genus *Meloidogyne* (1949). Christie (1945) reported nematicidal property of ethylene dibromide (EDB). Allen (1948) taught the world first formal university course in Nematology at the University of California, Berkeley. Oostenbrink (1950) wrote a book on "The Potato Nematode". Christie & Perry (1951) discovered that several ectoparasitic nematodes (*Xiphinema*, *Trichodorus*, *Belonolaimus*) are pathogenic.

Other scientists, past and present, who contributed significantly to Nematology are Ditlevsen, de Coninck, Hofmanner, Menzel, Schneider, Franklin, Goffart, Ritzema-Bos, Triffit, J.B. Goodey, Jones, Weischer, Seinhorst, Luc, Lamberti, Vinciguerra, Geraert, Ellenby, Nordbring-Hertz, Jansson, Croll, Krall, Van der Laan, Stone, Evans, Kerry, Southey, Nickle, Giebel, Loof, Gommers, A.H. Meyl, Esser, Wouts, Sikora, Moens, Benzooijen, Greco and many others.

European Society of Nematologists (ESN) was founded in 1955. In Wageningen, the Nematologists approved the formation of a new journal entirely on nematodes in the Third International Symposium on "Plant Nematodes and the Diseases They Cause" (30 June – 5 July, 1955). The journal was named Nematologica ..... the first issue of which was published in 1956 by E.J. Brill, Leiden. Thus, the first journal of its kind which is exclusively devoted to plant and soil nematodes came into existence. Later two more journals from Europe viz., 'Nematologia Mediterranea' (1973), Italy and 'Revue de Nematologie' (1978) from France were published. Now Nematologica and Revue de Nematologie have been merged in one journal entitled, 'Nematology'.

In the United States of America (USA), Leidy (1851) gave first free living nematodes. May (1888) first time observed the root-knot species, *Meloidogyne* spp. Other scientists who actively contributed in the later part of the nineteenth century were Atkinson (1889), Neal (1889), Halsted (1891),

Stone and Smith (1898). However, the real breakthrough in the development of nematology in USA came after the researches of Nathan Augustus Cobb (1859-1932) who joined the United States Department of Agriculture in 1907. He secured his Doctorate in Jena in 1889. His first paper on plant parasitic nematodes, "Tylenchus and Root Galls" appeared in the "Agricultural Gazette of New South Wales (1890). He studied minute details of plant parasitic nematodes and occupied much of his time, with special reference to those organs for which he coined new terminologies viz., amphids, phasmids, deirids. Among his writings "Contribution to a Science of Nematology" is the most outstanding. He made major discoveries in the areas of nematode taxonomy, morphology and methodology for research in nematology. Cobb proposed that plant parasitic and free living nematodes be removed from helminthology and be assigned to a new branch of science to be known as 'Nematology'. His laboratory manual, "Estimating the Nema Population of Soil" (1918) formed the basis for a large portion of the methods and apparatus used in nematology today. The outstanding work earned Cobb the title "Father of Nematology" in the United States. Associated with Cobb during those early eventful years was W.E. Chambers, artist and microscopist. He produced excellent illustrations of nematodes for the scientific publication of Cobb.

Among the early contemporaries of Cobb in the United States Department of Agriculture was Bessey. He worked on root-knot nematodes. His report (Bessey, 1911) included a review of the principal work done upto

that time and included considerable original research work. Cobb's other associates were J.R. Christie, G. Steiner, Chitwoods, A.L. Taylor, E.M. Buhrer, G.S. Cobb and F.E. Albin. There were many other scientists in the United States who made valuable and outstanding contributions during this time e.g. G.H. Godfrey, M.B. Linford and J.R. Watson etc.

After Cobb's death in 1932, G. Steiner succeeded Cobb in 1932. Steiner's (1949) publication, "Plant-parasitic Nematodes the Grower should know" introduced nematodes not only to the Growers, but did much to promote applied nematology. He got Distinguished Service Medal of the U.S. Department of Agriculture on his retirement in 1956. Taylor succeeded Steiner and contributed much throughout his life. "An Introduction to Nematology" by B.G. and M.G. Chitwood (1937), "Plant Nematodes, their Bionomics and Control" by Christie (1959) and "Principles of Nematology" by Thorne (1961) were classical books on nematodes contributed by U.S. scientists.

In the second half of the 20th century, nematology grew up fast and became a full fledge discipline of science with its own techniques, fields of research, text books, academic and scientific programmes. Other nematologists in the United States, past and present, included Raski, Cairns, Tarjan, Allen, Sasser, McBeth, Carter, Krusberg, Sayer, Mankau, Jenkins, Dropkin, Smart, Barker, Lownsbery, Veech, Good, Golden, Rodriguez-Kabana, Mai, Norton, Nickle, G.W. Bird, Ferris, Zuckerman, Maggenti, Fortuner, Eisenback Baldwin, Crow, Ley, Mc Sorley, Freckman, D.J. Chitwood and many others.

Late Dr. J.N. Sasser was a pioneer researcher and world authority on root-knot nematodes. He completed his Doctorate degree in 1953 entitled, "Identification and host-parasite relationships of certain *Meloidogyne* species and races". His students and other associates were among the first to study the physiological and biochemical aspects in plant parasitic nematodes and to employ molecular techniques in root-knot nematode taxonomy. By the mid 70s, he had conceptualized, organized and implemented his widely acclaimed, 'International *Meloidogyne* Project' (IMP) funded by United States Agency for International Development (USAID), aimed primarily at coordinating and promoting research on root-knot nematodes worldwide. The IMP also facilitated training programmes in nematology. Sasser's contributions to nematology are recognized widely. He was a multifaceted educator. He had the capacity to formulate hypothesis, address new problems and research areas and stimulate the interest of young scientists.

In 1969, Society of the Nematologists, North America (SON) started the publication of Journal of Nematology, later, 'Annals of Applied Nematology' was started in 1987 as supplement to the Journal of Nematology. The Organization of Tropical American Nematologists (OTAN), another American Society started publishing the 'Nematropica' in 1971.

There are so many great scientists who have done excellent work outside USA and Europe. They are A.D. Barker, J.E. Bosher, Wm. Newton, R.J. Hastings and Webster of Canada, Colbran, Wallace, Brown and A.F. Bird

of Australia. Nishizawa, Ishibashi and Ichinohe of Japan. Jatala of Peru, Maqbool and Ghaffar of Pakistan, Katan and Okayugi of Israel, E.M. Mousa of Egypt and many others. The 'Pakistan Journal of Nematology' was started in 1983 as an official organ of Pakistan Society of Nematologists. However, due to the lack of proper facilities, poor access to literature and scarcity of expertise the development of nematology in the developing countries was hampered.

In India, Barber (1901) reported root-knot nematode on tea for the first time in South India. Later Butler (1906) reported root-knot nematode on black pepper in Kerala. He (1913, 1919) also reported Ufra disease of rice caused by *Ditylenchus angustus*. Ayyar (1926, 1933, 1934) reported root-knot nematode infesting vegetables and other crops in South India. Dastur (1936) reported White tip disease of rice caused by *Aphelenchoides besseyi*. All these were important landmarks by themselves in India. However, plant nematology as a discipline is hardly fifty years old. Late Prof. Abrar M. Khan, joined the Department of Botany, Aligarh Muslim University (AMU), Aligarh in late forties after obtaining Doctorate from the University of Minnesota, USA under the guidance of Prof. E.C. Stakman, the doyen of Plant Pathology. He soon realized the importance of plant parasitic nematodes. Prof. Khan (1973) in his presidential address of first annual general body meeting on 27th March, 1973, at Indian Agricultural Research Institute (IARI), New Delhi pointed out in his own words:

"In one of my orchards, beds after beds of papaya seedlings were infected with leaf-curl virus. My brother asked me to suggest control measures. Knowing about the nature of disease, I recommended the eradication of the entire plantation. To my surprise the seedlings were not only infected with virus but their roots were full of galls of varying sizes, housing thousands of females of root-knot nematodes, Meloidogyne incognita. I looked for information in the literature about the diseases caused by nematodes in India. To my utter dismay, I could find out a very few references (Barber, 1905, Butler, 1913, Dastur, 1936). Dr. P.R. Mehta, the then Director of Plant Protection and Quarantine, visited me. I discussed with him the lack of interest which Indian scientists had about nematological problems. We resolved to undertake the work on nematodes. I persuaded my revered friend, Late Dr. M.A. Basir Khan, a well known taxonomist of insect-parasitic oxyuroid nematodes of the Department of Zoology, A.M.U., Aligarh to undertake the work on taxonomy of nematodes and we on our part confined our activities to applied aspect. Dr. M. Rafiq Siddiqi in the Department of Zoology under the supervision of M.A. Basir Khan and Dr. Asad Ahmad under my supervision in Botany Department were enrolled as Research Scholars. This is how the work in nematology was started at Aligarh" (Khan, 1974).

This was the period of mid-fifties. During this period a few scientists of Osmania University, Hyderabad and Indian Agricultural Research Institute (IARI), New Delhi independently started work on plant parasitic nematodes. M.R. Siddiqi of Zoology Department, A.M.U., Aligarh published his first paper in 1959 and Das of Osmania University in 1960. Since most of the scientists in India did not have a formal training in nematology, so Prof. A.M. Khan approached the Colombo Plan Authorities to depute the services of some eminent nematologists to give formal training in nematology to Indian workers. They deputed Dr. F.G.W. Jones, Head, Department of Nematology, Rothamsted Experimental Station, U.K. During his stay at Aligarh in 1961 Dr. Jones went to the South and detected the presence of Golden Cyst nematode of

potato, *Globodera rostochiensis*, a pest of great economic importance. In the words of Prof. Khan (1974) "If at all there was one single factor that triggered nematological research in India, I would say it was this discovery". By the joint effort of Prof. Khan and the scientists of IARI an International Nematology Course at IARI was organized in 1964 with the help of Rockfeller Foundation. Late Dr. F.G.W. Jones, late Dr. J.B. Goodey both of U.K. and Prof. D.J. Raski of California, USA were the distinguished resource persons for the course. Later, by the joint efforts of AMU and IARI seven training programmes entitled "South-East Asia Postgraduate Nematology Courses" of three months duration were organized in the years 1967-68, 1968-69, 1969-70, 1971, 1973 and 1975. International Agricultural Centre, Wageningen funded by The Dutch Government in addition to providing the equipment also lent the services of late Dr. M. Oostenbrink, Dr. Jan A. Van-Berkum and Mr. J.J. S'Jacob for the first course and that of Van Berkum and S'Jacob for the second and third courses. The subsequent courses were being run with the collaboration of Department of Botany, AMU Aligarh and the Division of Nematology, IARI, New Delhi. This is how nematology in India came to sound footings with the help of the British, Dutch and American scientists.

At Aligarh Professors Abrar M. Khan, S.K. Saxena, S.I. Husain, M.M. Alam, Dr. Asad Ahmad from the Botany Department and Dr. M.R. Siddiqi, Prof. M.S. Jairajpuri, Prof. S.H. Khan, Dr. E. Khan from Zoology Department were the early workers who contributed to nematology. Dr. Siddiqi later joined

Commonwealth Institute of Parasitology (CIP), England and Dr. E. Khan joined the Division of Nematology at IARI, Dr. Asad Ahmad went to Canada and no more concerned with nematology. Prof. Jairajpuri joined Zoological Survey of India (ZSI) and later became the Vice Chancellor of Maulana Azad National Urdu University, Hyderabad. He has enormously contributed on nematode taxonomy. Other nematologists at AMU, Dr. Q.H. Baqri, Professors Shahid Hasan Khan, Irfan Ahmad, Wasim Ahmad, Drs. M. Shakeel; M. Sarwat Sultan, A.L. Bilgrami and Ms. Qudsia Tehsin at Zoology Department, Professors M.W. Khan, Z.A. Siddiqi, M.M. Alam, M.F. Azam, A. Haseeb, Drs. M.M. Haque, A. Rashid, I. Mahmood, Zakiuddin, Rehanur Rehman, Akhtar H. Khan, A. Masood, M.R. Khan, T.A. Khan, Hisamuddin, A.A. Khan, Zaki A. Siddiqi and S.A. Tiyagi at Department of Botany, A.M.U., Aligarh have done enormous work on applied aspects.

Other eminent nematologists of India are Drs. A.R. Seshadri, S.K. Prasad, G. Swarup, D.R. Dasgupta, B.K. Goswami, D. Prasad, H.S. Gaur, S. Gill, from I.A.R.I., New Delhi, R.S. Singh from the University of Agriculture & Technology, Pantnagar, D.S. Bhatti, D.C. Gupta and H.K. Bajaj from HAU, Hissar, V.M. Das from Osmania University, Hyderabad, J.C. Edward from Agricultural Institute, Allahabad, Y.S. Rao from CRRI, Cuttack, Professors B.S. Yadav and A.U. Siddiqui from Maharana Pratap University of Agriculture & Technology, Udaipur, Dr. B.N. Mathur from Agricultural Experimental Station, Jaipur, Professors A.C. Verma and A. Hasan from N.D.

University of Agriculture, Faizabad, Dr. M. Luqman Khan from Y.S.P. University of Horticulture & Forestry Solan, Prof. P.C. Trivedi, Department of Botany, University of Rajasthan, Jaipur, Drs. D.J. Patel, GAU, Anand, R.M. Khan, CISH, Lucknow, S.S. Hussaini, Bangalore, P.K. Koshy, Kayangulam, Kerala and many others.

There are several important developments that led to the expansion of the science of nematology in India are:

1. The pioneer work in nematode survey and taxonomy at Aligarh, Hyderabad and New Delhi.
2. Ever increasing reports of nematode damage to a variety of crops like root-knot nematodes on vegetable crops, *Heterodera avenae* on wheat and barley, *Rotylenchulus reniformis* on castor, vegetable crops, pulses, grapevine, *Tylenchulus semipenetrans* on citrus.
3. The discovery of *Globodera rostochiensis* on potato in the Nilgiri hills.

Nematological Society of India was founded in 1969. The first General Body (GB) meeting of the Society was held under the chairmanship of the senior most nematologist Prof. Abrar M. Khan of the Department of Botany, Aligarh Muslim University, Aligarh. Some of the 70 nematologists who participated in the meeting was Prof. D.J. Raski of the University of California, Davis, California, USA. Initially 124 nematologists including students were enrolled as charter members of the Society. The Nematological Society of India (NSI) started publishing the Indian Journal of Nematology in 1971.

I have the priviledge to work with some of the most important nematologists of the country viz. Professors Abrar M. Khan, S.K. Saxena, S.I. Hussain, M. Mashkoor Alam and M. Farooq Azam. I started my research career in 1981 when I joined as a research scholar under the supervision of Prof. M. Mashkoor Alam in the Department of Botany, AMU, Aligarh. I got some Departmental financial assistance by the Aligarh Muslim University, Aligarh (UGC) in the form of Junior Research Fellowship (JRF) and Senior Research Fellowship (SRF). Then I joined All India Coordinated Research Project of University Grants Commission (UGC) as Senior Technical Assistance (1986-91). Later I was appointed as Lecturer in 1991 and then a Reader (equal to Associate Professor) in 2000 in Botany Department, AMU, Aligarh. In 1988 I attended an Advanced Training Course on Nematode Pest Identification at Department of Zoology, AMU, Aligarh. The course was organized by renowned nematode taxonomist Prof. M.S. Jairajpuri. I obtained my Ph.D. degree in 1986 working on "Studies on the effect of organic soil amendments on plant parasitic nematodes" under the guidance of Prof. M. Mashkoor Alam. The Ph.D. thesis was examined by eminent scientists, Dr. R. Rodriguez-Kabana, USA (Foreign Examiner) and Dr. P.K. Koshy, Head, Nematology Division, Central Plantation Crop Research Institute (Regional Station), Kayangulam, Kerala (Indian Examiner). I was elected a Fellow, Indian Botanical Society (IBS) in 1993, Fellow, Phytopathological Society of India (FPSI) in 1995 and Fellow, Nematological Society of India (FNSI) in

1998. I attended the first Afro-Asian Nematology Symposium at A.M.U., Aligarh (1992), and third Afro-Asian Nematology Symposium at Coimbatore (1998) organized by Afro-Asian Society of Nemtologists. There I got the opportunity of meeting and discussing various nematological problems with several eminent Nematologists of International repute. I have written a large number of book chapters, reviews and articles in special volumes on plant parasitic nematodes which have been published in India as well as abroad.

ECONOMIC IMPORTANCE OF PLANT PARASITIC NEMATODES

Plant parasitic nematodes, the "tiny but mighty soil borne organisms", unseen enemies are ubiquitos. This shows their economic importance. They are the most numerous animals on earth. Their recognition as serious pests of our crops came rather late. It was, by and large, the damage caused by these tiny organisms either overlooked or attributed to some other factors. They destruct directly or indirectly the crops. They either alone or in association with other micro-organisms cause diseases to plants resulting in reduced yield and quality of the produce. There is hardly any economic crop and for that matter any plant which does not have one or more nematode species feeding upon it as parasites. They are now firmly recognized as potentially serious constraints to crop productivity. They present some of the most difficult pest problems encountered in agricultural economy. Weischer (1967) has listed various ways by which plant parasitic nematodes affect the production and economy of crops.

(i) reduction in quality and quantity of crops,

(ii) need of fertilizer and water,

(iii) application of nematicides, and

(iv) impediment of production and trade by phytosanitary regulations.

Crop loss is defined as the difference between the attainable yield and the actual yield (Chiarappa, 1971). It is difficult, however, to determine the attainable yield because it depends on many cultural, environmental and pest factors. Actual yield is more easily measured as that obtained under prevailing pest pressure i.e. without protection. Although earlier reports on crop losses due to plant parasitic nematodes thought to be about 5% whereas, small farmers in the developing countries commonly experience much larger losses (Taylor & Sasser, 1978).

The degree of damage depends upon the population density of nematode(s) species, host suitability, locality, ecological factors, agronomic practices, control measures adopted, or more likely, a combination of all these conditions. The presence of multiple pathogens make diagnosis confusing and frequently resulting under assessment of the damage caused by the nematodes. There are numerous estimates of damage in crop production on worldwide or countrywide basis. Several billion $ worth of crop losses happen annually worldwide because of nematodes. Although accurate information on the extent of crop losses caused by plant parasitic nematodes is difficult to assess but several workers have interpreted approximate losses. For instance, Stapel

(1953) estimated an average annual loss of 50,000,000 Kroner (£ 2½ million) resulting from the attack of cereal root eelworm, *Heterodera avenae* in Denmark. Southey & Samuel (1954) found an average annual loss in potato to the tune of £ 2 million resulting from *Heterodera rostochiensis* in UK and Wales in 1949. Orr (1984), in Western Texas, estimated an annual loss of 85,600 bales in cotton yield due to *Meloidogyne incognita*. Some other estimates of annual losses caused by nematodes ranged from 250 million dollars (Hutchinson *et al.*, 1961) to 500 million dollars (Carins, 1955). The yearly losses estimated by the United States Department of Agriculture (USDA) in 16 crops amount to $ 372,335,000 (Taylor, 1967). The assessment of the Society of Nematologists Committee on crop losses indicates annual losses in the United States due to plant parasitic nematodes to the tune of $ 1,038,374,300 in field crops, $ 225,145,900 in fruit and nut crops, $ 266,989,100 in vegetable crops and $ 59,817,634 in ornamental crops (Anon, 1971). Later another such committee summarized the reports of crop losses due to plant-parasitic nematodes crop wise and state wise (Anon, 1987). Sasser & Freckman (1987) presented a report based on comprehensive worldwide survey. They reported a loss of more than $ 100 billion per annum due to plant parasitic nematodes. This figure may be more, as similar information from many countries, more particularly from developing countries is yet to come or if available, is not comprehensive. There are other reports too which have given

data about monetary losses in crops due to plant parasitic nematodes. Some of these have been given elsewhere in the thesis (Article 83).

In India also several workers have attempted to assess crop losses caused by plant parasitic nematodes. However, these are mostly confined to per cent losses. Probably Van Berkum & Seshadri (1970) were the first who calculated these losses in India in terms of money. They reported the loss of $ 10 million from 'ear cockle' disease caused by *Anguina tritici* in wheat and $ 8 million due to 'molya disease' caused by *Heterodera avenae* in the province of Rajasthan. Besides this, crop loss in coffee caused by *Pratylenchus coffeae* worth $ 3 million was also assessed. Handa *et al.* (1985) estimated the losses in barley due to *Heterodera avenae* to the tune of Rs. 1687-5911 per hectare. Several hundred crore rupees are lost due to nematode diseases annually in vegetable, cereal, pulse, oil seed, plantation and other crops. The major nematodes causing nationwide belong mainly to the genera *Meloidogyne*, *Heterodera*, *Rotylenchulus*, *Pratylenchus* and *Radopholus*.

The crop losses to agricultural production incurred by way of plant parasitic nematodes are of such magnitude that they require the use of various control measures. Historically Kühn (1881) in Germany, reported the first attempt to control the sugar beet cyst nematode, *Heterodera schachtii* by using carbon disulfide. Watson (1917) used calcium cyanamide in North Florida for controlling root-knot on tobacco. Matthews (1920) was first to report the effectiveness of Chloropicrin against root-knot nematode, while nematicidal

properties of methyl bromide were reported by Taylor & McBeth (1940). But real breakthrough in the development of nematicides came with the discovery of DD mixture by Carter (1943). Side by side other control measures such as biological control, crop rotation, organic amendments etc. also developed. Possibility of nematode biocontrol was suggested for the first time by Lohde (1874). This triggered researches on natural enemies of nematodes (Kühn, 1877; Zopf, 1888; Cobb, 1920; Thorne, 1927; Linford, 1937; Linford & Oliveira, 1938; Dollfus, 1946). The different nematode control strategies have been discussed in detail elsewhere in the thesis (Articles, 83-92).

ABOUT THE THESIS

The present thesis, which is based on my research work of almost two and half decades, is mainly concerned with the control of plant parasitic nematodes. These research efforts were directed keeping in view the needs of the country and also with the hope that these would unravel some of the basis of nematode control.

The different strategies were used for managing the nematodes including soil solarization, soil application of nematicides, root dip with systemic chemicals, organic soil amendments both conventional measures and unconventional waste organic matter, root dip and seed dressing with plant products and chemicals from promising organic soil amendments, screening of plant species and cultivars for locating source of resistance against nematodes, screening of various cropping sequences, effect of seasonal fluctuations on

nematode population, interculture of enemy plants etc. Studies were also directed to determine the mode of action of some of the control measures.

There are several review articles written by me as single or joint author on biological control of nematodes, seasonal fluctuations, soil solarization, crop loss assessment, cropping sequences, status of root-knot nematodes, potential of plant latices and a bibliography on soil solarization for the management of plant diseases and weeds.

In addition to above studies, the thesis also incorporates few articles on pathogenicity and interrelationships of nematodes. These aspects have some bearing on the studies pertaining to control aspect directly or indirectly. Brown & Kerry (1987) have also included these aspects in their book on nematode control.

The thesis embodies 81 research papers, 1 bibliography (77) and 10 book chapters/reviews (83-92) which are grouped in five sections as under:

SECTION A : SEASONAL FLUCTUATIONS

Knowledge about the mean density of nematode species inhabiting the rhizosphere of plants is of paramount importance before embarking a disease management programme. In perennial plants, it is necessary to have a data about the nematode populations during different seasons because of changes in environmental conditions. Environmental factors especially temperature, pH value and soil moisture may affect the nematode population in the soil and the host plant. Seasonal fluctuation studies play an important role in the

development of effective nematode management strategies around perennial crops. The plant parasitic nematodes have direct bearing on the extent of damage caused by them. Hence, the present investigations were undertaken.

In a seasonal fluctuation experiment around two perennial plants viz., lemon grass, *Cymbopogon flexuosus* and Pome granate, *Punica granatum* high population build up of plant parasitic nemtaodes was observed from February to May and again in September while low from June to August (2). Changes in nematode population were directly correlated with soil moisture (1).

In a one year seasonal fluctuation study some important plants viz., *Citrus*, mango, guava, *Zizyphus*, jambolan, grapes and Indian gooseberry were selected for the observation of nematode population changes around their roots. The data was taken at 10 cm (upper layer), 20 cm (middle) and 40 cm (lower) depths. The nematode population was higher at higher soil moisture level. Soil moisture and temperature directly affect the nematode population. The nematode population decline in drought conditions. The pH also indirectly affects the nematode population densities. By and large, the nematode population was higher in the upper 10 cm soil layer. It can be due to the presence of more feeder roots and rootlets at 10 cm depth (3-7). Based on the higher rate of nematode multiplication, Jujube and orange can be rated as good hosts and jambolan as moderate host for *Hoplolaimus indicus*, jujube and orange as poor hosts for *Helicotylenchus indicus*, orange as good host for

Tylenchorhynchus brassicae, jambolan and orange as poor hosts for *Tylenchus filiformis* (15).

The thesis also includes articles "Seasonal fluctuation of nematode population in relation to their environemt" (84) and "Assessment of crop losses caused by phytonematodes" (83).

SECTION B: PLANT REACTION, CROPPING SEQUENCES AND INTERCULTURE OF CROPS

Use of resistant/tolerant plant species and cultivars is considered as one of the ideal methods of nematode management. The studies pertaining to plant reaction to nematode infection were undertaken for creating source of resistance, if any. Nine species of *Amaranthus* were screened against *Meloidogyne incognita* and *Rotylenchulus reniformis* (9, 10). Only one speices showed highly resistant and one resistant reactions to *M. incognita* (9).

One of the aims of rotations of crops is to keep the populations of plant parasitic netmatodes below the damaging level. It provides comparatively safe and easy method of nematode management. However, suitability of crops for the area with respect to climatic conditions, as well as their economic feasibility are of paramount importance for embarking upon any rotational programme. Therefore, there is a constant need to search such sequences which are both detrimental to nematodes and acceptable to growers.

For studying the influence of different cropping sequences on plant parasitic nematodes, 25 different cropping sequences of vegetables, cereals,

fodder crops, oil crops etc. were selected. Growing susceptible hosts consequently increase the population of plant parasitic nematodes to noxious levels. Fallowing and growing mustard and some other plants caused substantial reduction in the population density of nematodes in most of the situations. *Brassica* sp. produced many compounds including isothiocyanates, thiocyanates and nitrites on hydrolysis. Some of the by products of these compounds on decomposition may be toxic to nematodes. It was found that no individual sequence was equally effective against all nematodes present in the soil. This was because of the fact that influence of different crops on nematodes varied in different sequences. In different cropping sequences in four fields, the population of maize cyst nematode, *Heterodera zeae* increased during maize cultivation. Besides fallow, highest decrease in the number of cysts was observed in wheat, Egyptian clover, mustard, barley, pigeon pea and maize (8). Reaction of crops varies from nematode to nematode (11-15).

Effect of interculture of Zinnia, *Zinnia elegans*; neem/margosa, *Azadirachta indica*; Persian lilac, *Melia azedarach*; different species of marigold/Tagetes spp. viz., *Tagetes lucida*, *T. minuta* and *T. tenuifolia* with tomato, eggplant, cabbage and cauliflower (17-20, 22, 24) on plant growth and soil population of commonly occurring nematodes was studied. The management of plant parasitic nematodes was found to be due to the toxic nature of root exudates of these plants (16, 21). The use of these plants in the

biological control of nematodes has been reviewed in article numbers 85, 89, 91.

SECTION C : NEMATICIDES AND ORGANIC SOIL AMENDMENTS

The test nematicides were found highly deleterious to plant parasitic nematodes and inhibitory on larval hatching (29, 32). Significant control of *M. incognita* was obtained by bare root dip treatment in dimethoate on tomato (25), in carbofuran, fenamiphos, ethoprophos, phorate on tomato and eggplant (38). In another experiment the control of *M. incognita* and *R. reniformis* was observed by bare-root dip treatment in triazophos/hostathion, carbosulfan/posse and rugby-10 on tomato and eggplant. As a consequence in the reduction of nematode infection plant growth of tomato and eggplant improved (37, 38).

Soil application in nursery, nematicides also caused significant reduction in the population of plant parasitic nematodes alongwith improvement in plant growth of tomato (31). Cost of treating the nursery soil is greatly reduced as the area of application is comparatively less. The plants raised from carbofuran, fenamiphos and phorate treated seeds of bottle gourd, *Lagenaria siceraria*; bitter gourd, *Momordica charantia* reduced the root-knot development caused by *M. incognita* and consequently the yield improved. Fenamiphos gave the best results followed by carbofuran and phorate (29). Similar results were also obtained while seed soaking of cowpea and okra in methyl demeton, dimethoate, UC-54229, acephate, monocrotophos and phosphamidon (39). In an integrated approach oil seed cakes of castor, *Ricinus*

communis; margosa/neem, *Azadirachta indica*; mustard, *Brassica campestris*; rocket salad, *Eruca sativa*; groundnut/peanut, *Arachis hypogaea* and two nematicides viz., carbofuran and aldicarb were used for the management of plant parasitic nematodes in deep (40 cm) and normal (20 cm) ploughed soil. All the additives were found highly satisfactory for the management of plant parasitic nematodes. The nematicides had a slight edge over the oil seed cakes. Deep (40 cm) ploughing was found to be a limiting factor. As a consequence in the reduction in nematode population the plant growth of tomato (28), carrot (30), okra (35) and eggplant (40) improved. The residual effect of oil seed cakes and nematicides persisted for longer durations, as they remain effective in subsequent crops even after a lapse of six months (28, 30, 35, 40).

Some of the nematicidal chemicals used in the above studies are now banned because of the associated environmental and health problems. But these studies were carried out when there was no restriction on the use of these chemicals.

Considerable work has been carried out on the management of plant parasitic nematodes with organic soil amendments. In a field study, oil seed cakes of castor, neem/margosa and chopped green tops of water hyacinth, *Eichhornia crassipes*, Mart, Solms. brought about significant reduction in nematode population highest being in neem treated field with a consequent increase in plant growth of berseem/Egyptian clover, *Trifolium alexandrinum* L. (33). In pot experiments soil amended with chopped leaves and flowers of

Cymbopogon flexuosus, *Aloe barbadensis*, *Ammi majus*, *Madhuca indica*, *Papaver rhoeas*, *Ruella tuberosa* and *Zinnia elegans* brought about significant inhibition in root-knot development caused by *Meloidogyne incognita* and an increase in plant growth of tomato (34). Neem leaf, seed powder, oil cake and two nematicides viz., carbofuran and phorate alone and in combination reduced the root-knot development and population of *R. reniformis*. As a result of reduction in nematode infection the plant growth improved (27, 41). Aqueous extracts of lemon grass, *C. flexuosus* was highly toxic to plant parasitic nematodes (26).

Soil amendments with oil seed cakes, leaves and sawdust of neem has given satisfactory control of plant parasitic nematodes in repeated tests (50). Significant control of *M. incognita* and *R. reniformis* was obtained on tomato and eggplant by bare-root dip treatment in leaf extracts of neem and Persian lilac. The damaging effects were marked and consequently improved plant growth. The root galling and nematode population were gradually decreased with an increase in the concentration and dip duration (46). Similar results were obtained with same treatments against *T. brassicae* on cabbage and cauliflower (49). This treatment also improved plant growth and water absorption efficiency of the roots of cabbage and cauliflower (49). Seed dressings with the extracts of neem and Persian lilac significantly controlled *M. incognita* and *R. reniformis* on tomato, eggplant and okra (44). Similarly seed dressings with neem chemicals like azadirachtin and nimbin, triterpenoids from neem were

effective against *M. incognita* and *R. reniformis* on tomato, eggplant and okra, and *T. brassicae* on cabbage and cauliflower (45, 47, 48, 51). Bare-root dip or seed dressings in leaf extracts of neem and neem chemicals tested induced some resistance to the test plants. Poor root-knot development and/or poor nematode multiplication could be attributed to poor penetration and later retardation in different activities of the second stage juveniles such as feeding and/or reproduction. Water extracts of different parts of neem and Persian lilac were highly deleterious to *Hop. indicus*, *Hel. indicus*, *R. reniformis*, *Tyl. filiformis*, *Trh. brassicae* and *M. incognita* larvae and inhibitory to larval hatching of *M. incognita* (42, 43). Some neem chemicals viz., azadirachtin, nimbidic acid, nimbin, kaempferol and quercetin were found highly deleterious to the test nematodes, however, to varying degree. These chemicals also caused significant inhibition in larval hatching of *M. incognita* (52).

Soil amendments of neem, *Azadirachta indica* or a related species Persian lilac, *Melia azedarach* controlled pest nematodes. Neem seeds were the most effective (54, 55, 59). Similar results were also obtained when the soil was amended with chopped leaves of *A. indica*, *T. patula*, *Ficus racemosa*, *F. bengalensis*, *F. virens* and *N. indicum* (54, 58).

Plant wastes of weeds and cultivated plants were evaluated for their potential in nematode control (68-72). In most of the cases soil amendments with plant wastes significantly suppressed nematode populations and improved

plant growth. This type of nematode control was considered economical, easy and pollution free.

Water hyacinth, *Eichhornia crassipes* one of the top ten widely distributed noxious weeds in India, is causing concern because it greatly interferes with agriculture, pisciculture, drainage, water sport, etc. Its disposal is yet another problem. Its possible utilization for the control of plant parasitic nematodes has been tested (71, 72). Soil amendments with chopped leaves and flowers as well as bare root dip treatment in its extracts have significantly controlled *M. incognita* and *R. reniformis* on tomato and eggplant (71), and *T. brassicae* on cabbage and cauliflower (72) with consequent improvement in plant growth. Extracts of water hyacinth were also found to be highly toxic to the nematodes (71, 72). Soil application of *Paecilomyces lilacinus* before inoculation of *Luffa aegyptica* plants was found to be more effective for the control of *M. incognita* (73).

It is a common practice that after flower harvest of marigold (*Tagetes* spp.) the plant residues are discarded. Therefore, in this regard the experiments were conducted to evaluate the feasibility of the use of marigold wastes against some important plant parasitic nematodes. Soil amendments with chopped floral parts, leaf and stem of marigold, *Tagetes* spp. viz., *Tagetes lucida*, *T. minuta* and *T. tenuifolia* gave greatest inhibition to the root-knot development and the population buildup of *R. reniformis* on tomato and eggplant (68), and *T. brassicae* on cabbage and cauliflower (68) and showed significant

improvement. General population of plant parasitic nematodes also significantly decreased when the soil was amended with the above mentioned marigold treatments on tomato and eggplant with a corresponding increase in plant growth (69). The improvement in plant growth may be partly due to the reduction in the population of plant parasitic nematodes and partly due to the fact that these additives also served as organic manures (68, 69). Water extracts of different parts of marigold, *Tagetes lucida* were highly deleterious to *M. incognita*, *R. reniformis*, *T. brassicae*, *Hop. indicus*, *Hel. indicus*, *T. filiformis* and inhibition in juvenile hatching (70).

Soil amendments with chopped shoot parts of latex bearing plants viz., *Artocarpus heterophyllus*, *Carica papaya*, *Ficus carica*, *F. elastica*, *F. glomerata*, *Ipomoea fistulosa*, *Nerium odorum* and *Tabernaemontana coronaria* significantly controlled *M. incognita* and *R. reniformis* on tomato and eggplant, *T. brassicae* on cabbage and cauliflower (62), and general population of plant parasitic nematodes on tomato and eggplant (66) with consequent improvement in plant growth (66). Similar results were also obtained when the nematode infested around the roots of tomato and eggplant was amended with chopped shoots of *Euphorbia neriifolia*, *E. tirucalli*, *Pedilanthus tithymaloides*, *Calotropis procera*, *Thevetia peruviana* (67). Water extracts of these latex bearing plants were highly deleterious to *Hop. indicus*, *Hel. indicus*, *R. reniformis*, *T. brassicae*, *T. filiformis*, *M. incognita* and

inhibitory to larval hatching of *M. incognita*, however, to varying extent (59, 60).

Seed dressing with plant latices of *Calotropis gigantea*, *C. procera*, *Euphorbia millii*, *E. neriifolia* and *E. tirucalli* significantly inhibited the root-knot development caused by *M. incognita* and multiplication of *R. reniformis* on tomato, eggplant and okra (63, 65), and *T. brassicae* on cabbage and cauliflower (64).

The thesis also includes articles on the "potential of plant latices in nematode control" (87, 88), Antagonistic plants (89), "Marigold (*Tagetes*): An auxiliary and nematode antagonistic plant" (91) and "Water hyacinth – a noxious weed" (92).

Soil solarization is a hydrothermal method of soil disinfestations using solar heat trapped and covered through transparent polyethylene mulch. It is used to control soil-borne pathogens. Despite some limitations, the studies of soil solarization may be effective either used singly or in combination with other factors. It has the potential for reducing plant parasitic nematodes as it is easy to apply, pollution free, economical and inexpensive.

In the present investigations soil solarization was integrated with oil cakes and nematicides. The oil cakes used were neem, castor and mustard while nematicides were carbofuran and aldicarb. The oil cakes and nematicides were efficacious in reducing nematode population than oil cakes alone. The effectiveness was enhanced when these treatments were combined with soil

solarization (74, 75) consequently the plant growth of tomato and eggplant improved (74, 75). Watered soil covered with polyethylene sheets during solarization had better effects on the reduction of nematode population (76).

Besides the above and other studies comprehensive bibliography on "Soil solarization for the management of plant diseases and weeds (77) and articles, "Management of plant parasitic nematodes by soil solarization" (90) and "Status of root-knot nematode in Uttar Pradesh, India" (81) have also been prepared.

SECTION D : PATHOGENICITY AND INTERRELATIONSHIPS

Some other observations were conducted to investigate the effect of plant parasitic nematodes on plant growth and water absorption efficiency of roots. It was observed that the plant growth and pollen fertility as well as water absorption capacity was significantly retarded due to infection of the root-knot, reniform and cyst nematodes infecting pigeon pea seedlings (80). There was a positive correlation between the reduction in plant growth, pollen fertility and water absorption efficiency. An increase in initial inoculum level of nematodes resulted in corresponding decrease in plant growth (80).

Root-rot fungus, *Rhizoctonia solani* and the nematodes *M. incognita*, *R. reniformis* and *T. brassicae* significantly reduced plant growth of tomato, eggplant, chilli and papaya when inoculated separately, however, a synergistic effect was observed in plants inoculated with the fungus and either of the nematodes (78). Similar trend was noted in case of reduction in water

absorption capability of roots. The presence of the root-rot fungus, on the other hand, had an antagonistic effect on the multiplication of the nematode. Similar results were also obtained in okra inoculated with *R. solani* and/or *M. incognita* and *R. reniformis* (79).

Higher number of fungal species and nematode population was observed in the rhizoshpere of okra/lady finger, *Abelmoschus esculentus* plants infected with Yellow Vein Mosaic Virus (YVMV) in comparison to their healthy counterparts. Deep ploughing (40 cm deep of soil) had an adverse effect on fungal species and nematode population. Plant growth was retarted in YVMV infected plants. But the deep ploughing brought about significant improvement in plant growth (81). *M. incognita* and Brinjal Mosaic Virus together caused more damage to brinjal plants than alone (82).

SECTION E : BOOK CHAPTERS/REVIEWS

In addition to the above mentioned research papers some Book Chapters/Reviews and a bibliography have been included as supplement.

There are ten chapters/reviews (83-92) and one bibliography (77) which have been written by me as single or joint author. Out of ten chapters, 9 chapters have been published (Chapter No.83-91) in various books and one chapter is unpublished (92). Chapter number 83 and 86 are introductory in nature. While chapter number 84 and 85 has discussed the various control strategies of nematodes. Chapter numbers 87, 88, 91 and 92 give broadlines of biological control of plant parasitic nematodes. Antagonistic plants in general

and neem in particular have been discussed in chapter number 89. Bibliography is on "Soil solarization for the management of plant diseases" (77). Special feature of the book chapters is that its substantial portion is based on the personal experimentation and experiences of the authors.

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