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A comprehensive study on the distribution, species diversity, population dynamics, and impact of plant-parasitic nematodes on vegetable crops in upper doab region (Uttar Pradesh), using advanced statistical approaches to evaluate crop susceptibility, environmental influences, yield loss, and sustainable management practices

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Abstract

Nematode infestation represents a major constraint to vegetable production, particularly in intensively cultivated regions such as Upper Doab Region of Uttar Pradesh, India. The present study was undertaken to assess the distribution, intensity, and impact of plant-parasitic nematodes across five main sites of Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, Hathras) and eight economically important vegetable crops. Field surveys, soil and root sampling, and laboratory identification revealed the predominance of root-knot nematodes, particularly *Meloidogyne incognita*. Statistical analysis, including ANOVA, correlation, and regression, demonstrated significant variation in infestation among crops and locations ($p < 0.05$), with brinjal and tomato identified as the most susceptible crops. A strong positive correlation ($r = 0.94$) was observed between infestation and yield loss, indicating a direct impact on productivity. Environmental factors such as soil type, irrigation, cropping pattern, and crop duration significantly influenced nematode dynamics. The Species Dominance Index confirmed *M. incognita* as the most destructive species, while the Composite Vulnerability Index ranked brinjal as the most affected crop. Economic analysis revealed substantial financial losses, particularly in high-value crops. The study highlights the urgent need for integrated nematode management strategies, including crop rotation, resistant varieties, and sustainable soil practices, to mitigate yield losses and enhance agricultural productivity in the region.

Keywords: Nematode infestation, *Meloidogyne incognita*, vegetable crops, Upper Doab Region, yield loss, root-knot nematode, soil factors, crop susceptibility, integrated pest management

Introduction

Agriculture plays a pivotal role in the socio-economic structure of rural India, particularly in districts like Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, Hathras) in western Uttar Pradesh, where a large proportion of the population depends on farming for livelihood. The region is characterized by fertile alluvial soils, a semi-arid to sub-humid climate, and diversified cropping systems that include both cash crops and food crops. Among these, tobacco and a wide range of vegetables constitute important commercial crops due to their high economic returns and market demand. However, the productivity and quality of these crops are significantly threatened by a variety of biotic stresses, among which plant-parasitic nematodes represent a major yet often overlooked constraint. Nematodes are microscopic, unsegmented roundworms belonging to the phylum Nematoda. They are ubiquitous in soil ecosystems and occupy diverse ecological niches. While many nematodes are beneficial, a significant number are plant-parasitic and cause severe damage to crops by feeding on plant roots, stems, leaves, and even seeds. These phytoparasitic nematodes are responsible for considerable yield losses worldwide, estimated to affect nearly 10% of global crop production annually. Their impact is particularly

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pronounced in intensively cultivated agricultural systems, such as those found in Upper Doab Region where continuous cropping and limited crop rotation create favorable conditions for nematode proliferation.

In India, nematode infestations have been reported to cause substantial yield reductions in horticultural and field crops. Studies indicate that plant-parasitic nematodes can result in an average annual loss of around 19.6% in agricultural production, with even higher losses—sometimes exceeding 60%—under intensive cultivation systems such as vegetable farming. These losses are often underestimated because nematode damage typically occurs below ground and does not always produce conspicuous above-ground symptoms. Consequently, infestations frequently go unnoticed until significant economic damage has already occurred.

Tobacco (*Nicotiana tabacum* L.) is one of the most important commercial crops grown in various parts of India, including pockets of Uttar Pradesh. It is highly susceptible to a wide range of pests and diseases, including nematodes. Research has shown that nematode infestation in tobacco can occur both in nursery stages and in transplanted crops, with incidence levels reported as high as 59.4% in nurseries and 52.9% in field conditions. Among the nematodes affecting tobacco, species such as root-knot nematodes (*Meloidogyne* spp.) and tobacco cyst nematode (*Globodera tabacum*) are of particular importance. These nematodes invade the root system, causing the formation of galls or cysts, leading to impaired nutrient uptake, stunted growth, and reduced leaf quality. In severe cases, they can drastically reduce yield and render the crop economically unviable.

Vegetable crops, including tomato, brinjal, chili, okra, cucurbits, and leafy greens, are equally vulnerable to nematode attack. Root-knot nematodes (*Meloidogyne* spp.) are considered the most destructive group affecting vegetable crops worldwide. They infect plant roots and induce the formation of characteristic root galls, which interfere with the plant's ability to absorb water and nutrients. Other important nematodes associated with vegetables include lesion nematodes (*Pratylenchus* spp.), cyst nematodes (*Heterodera* spp.), reniform nematodes (*Rotylenchulus* spp.), and stem and bulb nematodes (*Ditylenchus* spp.). These nematodes not only reduce crop yield but also predispose plants to secondary infections by fungi and bacteria, thereby compounding the damage.

The agro-climatic conditions of upper Doab Region of western Uttar Pradesh, including Kasganj, Etah, Aligarh, Badaun, Hathras district, are particularly conducive to the survival and multiplication of nematodes. The region experiences high soil temperatures, often ranging between 25°C and 38°C, along with intermittent moisture conditions, which create an ideal environment for nematode activity. Additionally, intensive cropping practices, monoculture, and the use of infested planting material further contribute to the buildup of nematode populations in the soil. The movement of contaminated soil through irrigation water, farm implements, and human activities facilitates the rapid spread of these pests across fields and regions. Despite their economic significance, nematodes have historically received less attention compared to other plant pathogens such as fungi, bacteria, and insects. This is largely due to their microscopic size, cryptic nature, and the complexity involved in their detection and identification. Accurate identification of nematode species is crucial for effective management, as different species vary in their host range, pathogenicity, and response to control measures. Traditional identification methods based on morphological characteristics

require specialized expertise and are time-consuming. However, recent advances in molecular techniques have enhanced the accuracy and efficiency of nematode diagnostics.

A systematic survey and identification of nematode pests associated with tobacco and vegetable crops in Upper Doab Region is therefore of paramount importance. Such a study would provide valuable baseline data on the diversity, distribution, and population dynamics of nematodes in the region. It would help in identifying the predominant species responsible for crop damage and assessing their severity under local agro-ecological conditions. This information is essential for developing targeted and sustainable nematode management strategies. The survey component of the study involves the collection of soil and root samples from different agricultural fields across various locations in Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, Hathras). These samples are then processed in the laboratory to extract nematodes using standard techniques such as the Baermann funnel method, Cobb's sieving and decanting method, or centrifugal flotation. The extracted nematodes are examined under a microscope for identification based on morphological features such as body shape, stylet structure, esophageal glands, and reproductive organs. In advanced studies, molecular tools such as polymerase chain reaction (PCR) and DNA sequencing may be employed for precise species identification. Identification of nematodes is not only important for understanding their taxonomy but also for correlating specific species with particular crop symptoms and damage patterns. For instance, root-knot nematodes cause visible galling on roots, while lesion nematodes produce necrotic lesions and root decay. Stem and bulb nematodes lead to swelling and distortion of plant tissues. Recognizing these symptoms in the field, combined with laboratory identification, enables accurate diagnosis of nematode problems.

The significance of this study extends beyond academic interest. It has practical implications for farmers, extension workers, and policymakers. By identifying the major nematode pests affecting tobacco and vegetable crops in Upper Doab Region, appropriate management strategies can be recommended. These may include cultural practices such as crop rotation, use of resistant varieties, soil solarization, organic amendments, and biological control agents. Integrated nematode management (INM) approaches that combine multiple strategies are particularly effective in reducing nematode populations and minimizing crop losses.

Furthermore, the findings of such a survey can contribute to the development of region-specific pest management guidelines and support sustainable agricultural practices. In the context of increasing demand for safe and environmentally friendly farming methods, understanding the ecology and behavior of nematodes becomes even more critical. Effective nematode management not only enhances crop productivity but also improves soil health and long-term agricultural sustainability. Nematode pests represent a significant but often underestimated threat to commercial tobacco and vegetable cultivation in Upper Doab Region. Their hidden nature, wide host range, and ability to cause substantial yield losses necessitate systematic investigation. A comprehensive survey and identification study serves as a foundational step toward understanding the nematode problem in the region and developing effective management strategies. By bridging the gap between scientific research and practical application, such studies play a crucial role in ensuring sustainable agricultural development and improving the livelihoods of farmers in the region.

Ganga–Yamuna Upper Doab Region: Area and Nematode Infestation in Crops

The Ganga–Yamuna Upper Doab is one of the most agriculturally significant regions of northern India, situated between the rivers Ganga River and Yamuna River. This fertile tract includes districts such as Kasganj, Etah, Aligarh, Badaun, and Hathras. The region forms a part of the Indo-Gangetic plains, known for its high soil fertility, intensive cultivation, and diverse cropping systems. Agriculture here is highly developed, supporting both subsistence and commercial farming, including crops like wheat, rice, vegetables, tobacco, and pulses.

Agro-Climatic and Soil Characteristics

The Upper Doab region is characterized by deep alluvial soils, primarily sandy loam to clay loam in texture, which are highly suitable for crop production. The climate is subtropical, with hot summers and cool winters, and temperatures ranging between 20°C and 40°C during most cropping seasons. Adequate irrigation through canals and tube wells ensures continuous cropping throughout the year. However, these same favorable conditions—especially warm temperatures, moisture availability, and loose soil structure—also create an ideal environment for the growth and multiplication of plant-parasitic nematodes. Agriculture in districts like Aligarh and Kasganj is highly intensive, with cropping patterns such as rice–wheat rotation, vegetable–vegetable sequences, and tobacco-based systems. Farmers often cultivate two to three crops annually, leading to high cropping intensity. While this enhances productivity and income, it also results in continuous host availability for nematodes. The frequent use of the same fields for susceptible crops, along with limited crop rotation, contributes to the buildup of nematode populations in the soil. Plant-parasitic nematodes are widely distributed across the Upper Doab region. Surveys conducted in districts such as Aligarh and Hathras have revealed high infestation levels, particularly in vegetable and rice crops. The widespread occurrence of nematodes is attributed to favorable environmental conditions and intensive agricultural practices. Since these microscopic organisms inhabit soil and plant roots, their presence often goes unnoticed until significant crop damage has occurred.

Nematode Infestation in Vegetable Crops

Vegetable cultivation is widespread in Upper Doab Region due to its high profitability and market demand. However, these crops are highly susceptible to nematode infestation. Studies conducted in western Uttar Pradesh reveal that plant-parasitic nematodes are widely distributed and cause significant economic losses in vegetable crops. The average yield loss due to nematode infestation has been reported to be around 23.7%, with losses reaching up to 43% in crops like brinjal (eggplant) and 40% in tomato. The most common nematode species affecting vegetable crops in this region include:

- Root-knot nematodes (*Meloidogyne incognita* and *Meloidogyne javanica*)
- Reniform nematode (*Rotylenchulus reniformis*)
- Lesion nematode (*Pratylenchus* spp.)
- Stunt nematode (*Tylenchorhynchus* spp.)

Among these, root-knot nematodes are the most destructive. They cause the formation of galls on roots, disrupting water and nutrient uptake. As a result, infected plants exhibit symptoms such as stunted growth, yellowing of leaves, wilting, and reduced fruit size. In severe infestations, the entire crop may fail.

Nematode Infestation in Tobacco Crops

Tobacco is an important commercial crop in regions adjoining Upper Doab Region which is known as a major tobacco-producing center in northern India. Similar cultivation practices and soil conditions exist in Kasganj, Etah, Aligarh, Badaun, Hathras, making tobacco crops equally vulnerable to nematode attack. Nematodes affecting tobacco primarily include:

- Root-knot nematodes (*Meloidogyne* spp.)
- Cyst nematodes (*Globodera* spp.)
- Reniform nematodes (*Rotylenchulus reniformis*)

These nematodes attack the root system, leading to gall formation, reduced root efficiency, and poor nutrient absorption. In tobacco, this results in:

- Reduced leaf size and quality
- Poor curing characteristics
- Lower nicotine content
- Significant reduction in market value

Infestation can begin at the nursery stage and continue after transplantation, making early detection and management critical.

Mechanism of Crop Damage

Nematodes damage crops through direct and indirect mechanisms. Direct damage occurs when nematodes feed on plant tissues using a specialized stylet, puncturing cells and extracting nutrients. Indirect damage occurs when feeding creates entry points for secondary pathogens such as fungi and bacteria, leading to complex disease conditions. For example, species like the stem and bulb nematode (*Ditylenchus dipsaci*) can cause tissue swelling, distortion, and rotting in host plants, ultimately reducing crop quality and yield. Similarly, root-knot nematodes interfere with vascular tissues, severely affecting plant growth and productivity.

Factors Contributing to Nematode Infestation in Upper Doab Region

Several factors contribute to the high incidence of nematodes in Upper Doab Region:

1. Continuous cultivation of the same crops, especially vegetables and tobacco, increases nematode population density.
2. Nursery seedlings and transplants often carry nematodes, facilitating their spread to new fields.
3. Flood irrigation helps in dispersing nematodes across fields.
4. Farmers often misidentify nematode symptoms as nutrient deficiencies or other diseases, delaying proper management.
5. Sandy loam soils with adequate moisture support nematode survival and reproduction.

Symptoms of Nematode Infestation in Crops

Common field symptoms observed in Upper Doab Region include:

- Root galls and deformities
- Yellowing and wilting of plants
- Reduced plant vigor
- Patchy crop growth in fields
- Poor yield and inferior quality produce

Because these symptoms are often non-specific, laboratory analysis of soil and root samples is essential for accurate diagnosis.

Review of Literature

Plant-parasitic nematodes are among the most destructive soil-borne pathogens affecting agricultural productivity worldwide. Their impact is particularly severe in vegetable cropping systems, where intensive cultivation practices create favorable conditions for nematode proliferation. Early studies by Sasser and Carter (1985) ^[28] highlighted the global significance of nematodes, estimating substantial crop losses due to root-knot nematodes. Similarly, Norton (1978) ^[23] emphasized the ecological adaptability of nematodes, which enables them to thrive across diverse agro-climatic conditions. Among the various nematode species, root-knot nematodes (*Meloidogyne spp.*) are considered the most economically important due to their wide host range and ability to cause severe root damage. According to Jones *et al.* (2013) ^[15], these nematodes are ranked among the top ten plant-parasitic nematodes worldwide. Their pathogenicity is primarily associated with the formation of root galls, which disrupt water and nutrient uptake, leading to stunted growth and reduced yields (Hussey & Janssen, 2002) ^[13]. The dominance of *Meloidogyne incognita* in vegetable crops has been widely reported in India and other tropical regions (Moens *et al.*, 2009) ^[21]. Several studies have documented the relationship between nematode population density and crop yield loss. Barker and Olthof (1976) ^[3] established that yield reduction is directly proportional to nematode density, a finding further supported by Viaene and Abawi (1998) ^[36], who identified economic threshold levels for nematode damage. In vegetable crops such as tomato and brinjal, yield losses can exceed 40% under severe infestation (Kumar & Singh, 2019) ^[19].

Environmental factors play a crucial role in influencing nematode distribution and activity. Soil texture, moisture, and temperature significantly affect nematode survival and reproduction. Prot and Van Gundy (1981) ^[26] demonstrated that sandy soils favor nematode movement and infection, while heavier soils restrict their activity. Similarly, irrigation practices have been shown to enhance nematode spread by increasing soil moisture (Noling, 2012) ^[22]. Seasonal variations also influence nematode dynamics, with higher temperatures accelerating their life cycle (Trudgill & Blok, 2001) ^[34]. Cropping patterns and agricultural practices are equally important determinants of nematode infestation. Continuous cultivation of susceptible crops leads to population buildup, whereas crop rotation with non-host species can effectively reduce nematode density (Ploeg, 2001) ^[25]. The role of weeds as alternate hosts has also been highlighted, as they provide a reservoir for nematode survival during off-seasons (Khan & Kim, 2007) ^[17]. Soil fertility and organic matter content have a complex relationship with nematode populations. While high nutrient levels promote plant growth, they may also enhance nematode reproduction by increasing root biomass (Oka, 2010) ^[24]. However, certain organic amendments, such as neem cake and compost, have been found to suppress nematodes through biological and chemical mechanisms (Akhtar & Malik, 2000) ^[11].

Advancements in statistical analysis have enabled researchers to better understand nematode dynamics and their impact on crop productivity. Techniques such as ANOVA, regression analysis, and correlation studies are widely used to assess the significance of various factors influencing infestation (Zasada *et al.*, 2010) ^[39]. Composite indices, such as the Species Dominance Index and Crop Vulnerability Index, provide integrated measures of nematode impact and crop susceptibility. In the Indian context, several studies have reported widespread nematode infestation in vegetable crops. Jain *et al.* (2007) ^[14] estimated national crop

losses due to nematodes, while Sharma and Sharma (2015) ^[29] documented their distribution across different agro-climatic zones. Regional studies in Uttar Pradesh have also highlighted the prevalence of *Meloidogyne spp.* in vegetable-growing areas (Yadav & Bhatti, 2018) ^[38]. Despite extensive research, nematode management remains a challenge due to their complex life cycle and adaptability. Integrated approaches combining cultural, biological, and chemical methods are considered most effective (Sikora & Fernández, 2005) ^[30]. Recent studies emphasize the importance of sustainable practices, including crop rotation, resistant varieties, and soil health management, to reduce reliance on chemical nematicides (De Waele & Elsen, 2007) ^[9]. Overall, the literature underscores the significant impact of plant-parasitic nematodes on vegetable production and highlights the need for region-specific studies.

The present research builds upon these findings by providing a detailed analysis of nematode infestation in Upper Doab Region comprising Kasganj, Etah, Aligarh, Badaun, Hathras district, integrating field data with advanced statistical methods to identify key factors influencing infestation and to develop effective management strategies.

Research Methodology

The present study was conducted to assess and analyze nematode infestation in major vegetable crops across selected locations in the Upper Doab Region of Uttar Pradesh. A systematic and quantitative research approach was adopted to ensure reliable data collection, statistical validation, and meaningful interpretation. Five Main agricultural sites—Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, Hathras), were selected based on their prominence in vegetable cultivation. These sites represent diverse agro-ecological conditions within the district, including variations in soil type, irrigation practices, and cropping patterns. Eight commonly cultivated vegetable crops were included in the study: tomato, brinjal, okra, potato, cabbage, bottle gourd, bitter melon, and spinach. These crops were selected due to their economic importance and known susceptibility to plant-parasitic nematodes.

Field surveys were conducted using a random sampling method during the cropping season. From each site, multiple fields were selected, and soil and root samples were collected from the rhizosphere zone (0–20 cm depth). Approximately 10–15 samples per crop per site were collected to ensure representativeness. Nematodes were extracted from soil samples using the Baermann funnel technique and Cobb's sieving method. Root samples were examined for galling symptoms, and nematodes were identified up to species level based on morphological characteristics under a microscope. Key species identified included *Meloidogyne incognita*, *Meloidogyne javanica*, *Rotylenchulus reniformis*, and *Pratylenchus spp.* The following parameters were recorded:

- Percentage of infestation (field-level occurrence)
- Nematode population density (J2/100 cc soil)
- Root Gall Index (0–5 scale)
- Yield loss estimation (%)
- Soil type, irrigation level, cropping pattern, and organic matter content

Data Analysis

Nematode infestation has emerged as a major constraint in vegetable production systems, particularly in intensively cultivated regions such as Upper Doab Region of Uttar Pradesh. Plant-parasitic nematodes, especially root-knot nematodes (*Meloidogyne spp.*), cause significant damage to a wide range of

vegetable crops by affecting root structure, nutrient uptake, and overall plant vigor. The resulting yield losses not only reduce agricultural productivity but also impose serious economic burdens on farmers. The increasing prevalence of nematodes in vegetable-growing areas is closely linked to continuous cropping, intensive irrigation, and the cultivation of susceptible crop varieties. Despite their microscopic size, nematodes have a profound impact on crop health, often remaining undetected until severe damage has occurred. Therefore, understanding their distribution, intensity, and impact across different crops and environmental conditions is essential for effective management. The present study aims to analyze nematode infestation patterns across selected sites and vegetable crops in Upper Doab Region using statistical tools. By examining relationships between infestation levels, yield loss, environmental factors, and species composition, the study seeks to identify the most affected crops, dominant nematode species, and high-risk areas. This analysis provides a scientific basis for developing targeted and sustainable nematode management strategies.

Table 1: Spatial Distribution and Comparative Analysis of Nematode Infestation (%) Across Major Vegetable-Growing Sites in Upper Doab Region

Site	Infestation%
Kasganj,)	72%
Etah	68%
Badaun	74%
Aligarh	70%
Hathras	66%

Table 1 presents the percentage of nematode infestation recorded across five major vegetable-growing districts of the Upper Doab region, namely Kasganj, Etah, Badaun, Aligarh, and Hathras. The infestation percentage represents the proportion of sampled agricultural fields exhibiting the presence of plant-parasitic nematodes, particularly root-knot nematodes (*Meloidogyne* spp.), during the survey period. This table aims to highlight the spatial variation in infestation intensity and identify major hotspots of nematode prevalence across the region. The site-wise distribution of nematode infestation indicates a consistently high prevalence across all surveyed districts, ranging from 66% to 74%. Among the five districts, Badaun recorded the highest infestation level (74%), followed by Kasganj (72%) and Aligarh (70%). Etah showed a moderately high infestation (68%), while Hathras exhibited the lowest infestation level (66%). Despite minor variations, the relatively narrow range suggests that nematode infestation is not restricted to specific localities but is widespread and endemic throughout the Upper Doab region. The higher infestation levels observed in Badaun and Kasganj may be attributed to intensive vegetable cultivation practices, continuous cropping systems, and frequent irrigation, all of which create favorable conditions for nematode proliferation. The predominance of sandy loam soils in these districts further facilitates nematode mobility and root penetration, thereby increasing infection rates. Additionally, the limited adoption of crop rotation and the continuous cultivation of susceptible crops such as tomato and brinjal contribute significantly to nematode population buildup. In contrast, the comparatively lower infestation recorded in Hathras may indicate relatively improved agronomic practices, such as better crop rotation, soil management, or lower cropping intensity. However, even the lowest infestation level (66%) remains substantially high, underscoring the severity and widespread nature of the problem

across the entire region. From a broader perspective, the uniform distribution of nematode infestation across all districts emphasizes the need for region-wide management strategies rather than isolated, site-specific interventions. Integrated nematode management approaches—including the use of resistant cultivars, organic soil amendments, biological control agents, and improved cultural practices—are essential for reducing infestation levels. Furthermore, strengthening farmer awareness and extension services is crucial to effectively address this persistent agricultural challenge.

Table 2: Crop-wise Assessment of Nematode Infestation (%) in Selected Vegetable Crops and Their Relative Susceptibility in the Upper Doab Region Agro-Ecosystem

Crop	Infestation%
Tomato	80%
Brinjal	85%
Okra	78%
Potato	72%
Cabbage	60%
Bottle gourd	75%
Bitter gourd	45%
Spinach	55%

Table 2 illustrates the percentage of nematode infestation observed across eight commonly cultivated vegetable crops in the Upper Doab Region region, namely tomato, brinjal, okra, potato, cabbage, bottle gourd, bitter gourd, and spinach. The infestation percentage represents the proportion of plants within each crop showing symptoms of nematode infection, such as root galling, stunted growth, and reduced vigor. This table aims to compare host susceptibility and identify highly vulnerable crops within the regional cropping system. The crop-wise analysis of nematode infestation reveals significant variation in susceptibility among different vegetable crops. Brinjal (85%) and tomato (80%) exhibit the highest infestation levels, indicating their high susceptibility to root-knot nematodes, particularly *Meloidogyne incognita*. These crops provide ideal conditions for nematode development due to their extensive root systems, longer growth duration, and continuous cultivation cycles. As a result, they act as major reservoirs for nematode populations, contributing to the persistence and spread of infestation in the region. Okra (78%) and bottle gourd (75%) also show relatively high infestation levels, suggesting moderate to high susceptibility. Potato (72%) falls within a similar range, indicating that root and tuber crops are also significantly affected. In contrast, cabbage (60%) and spinach (55%) show moderate infestation levels, which may be attributed to partial resistance or less favorable root structures for nematode colonization. Bitter gourd records the lowest infestation (45%), suggesting relative tolerance or resistance. This crop may possess certain biochemical or morphological traits that limit nematode penetration and reproduction. Such crops can play an important role in crop rotation strategies aimed at reducing nematode populations. The observed variation highlights the critical role of crop selection in nematode management. The predominance of highly susceptible crops like brinjal and tomato in the cropping system intensifies nematode pressure and leads to cumulative soil infestation over time. Therefore, incorporating less susceptible crops, such as bitter gourd and cabbage, into crop rotations can significantly reduce nematode load. The findings emphasize the need for strategic crop planning and the adoption of resistant varieties to mitigate nematode-related losses in

vegetable production systems.

Table 3: Site-wise Variation in Nematode Population Density (J2 per 100 cc Soil) and Its Implications for Infestation Intensity

Site	Density
Kasganj	650
Etah	580
Aligarh	720
Badaun	690
Hathras	540

Table 3 presents the variation in nematode population density, expressed as second-stage juveniles (J2) per 100 cc of soil, across five major districts of the Upper Doab region, namely Kasganj, Etah, Badaun, Aligarh, and Hathras. The population density of nematodes is a critical indicator of infestation intensity and potential crop damage. This table aims to assess spatial variation in nematode abundance and its implications for infestation severity in vegetable cropping systems. The data reveal considerable variation in nematode population density across districts, ranging from 540 to 720 J2 per 100 cc of soil. Among the districts, Badaun recorded the highest nematode density (720 J2), followed by Aligarh (690 J2) and Kasganj (650 J2), while Etah (580 J2) and Hathras (540 J2) exhibited comparatively lower densities. This distribution pattern closely corresponds with infestation levels observed in earlier analyses, confirming that higher nematode population densities are associated with increased infestation intensity. The elevated nematode density in Badaun and Aligarh may be attributed to intensive vegetable cultivation, continuous cropping practices, and favorable soil conditions such as sandy loam texture, which facilitate nematode survival, movement, and reproduction. Frequent irrigation in these districts further enhances nematode activity by maintaining optimal soil moisture conditions. In contrast, the relatively lower densities observed in Hathras and Etah may reflect differences in cropping intensity, soil management, or irrigation practices. High nematode population density directly contributes to severe root damage, particularly through gall formation caused by root-knot nematodes (*Meloidogyne* spp.). This leads to impaired water and nutrient uptake, ultimately affecting plant growth and productivity. Therefore, population density serves as a reliable predictor of potential crop loss and overall infestation severity.

Table 4: Comparative Evaluation of Yield Loss (%) in Major Vegetable Crops Attributed to Plant-Parasitic Nematode Infestation

Crop	Yield Loss%
Tomato	40%
Brinjal	43%
Okra	38%
Potato	32%
Cabbage	6%
Bottle gourd	35%
Bitter gourd	4%
Spinach	20%

Table 4 presents the estimated percentage of yield loss in selected vegetable crops due to nematode infestation across the Upper Doab region, comprising Kasganj, Etah, Aligarh, Badaun, and Hathras districts. Yield loss values are calculated based on comparative observations between infected and relatively healthy plants, taking into account parameters such as plant growth, fruit size, and overall productivity. This table aims to quantify the economic impact of nematode infestation and

identify crops most severely affected in terms of yield reduction. The analysis of yield loss provides important insights into the economic consequences of nematode infestation in the region. Among the studied crops, brinjal exhibits the highest yield loss (43%), followed by tomato (40%) and okra (38%). These significant losses are primarily associated with severe root galling and disruption of water and nutrient uptake caused by root-knot nematodes. Since these crops are widely cultivated and economically important, such high levels of yield reduction can substantially affect farmers' income and regional vegetable production. Bottle gourd (35%) and potato (32%) also show considerable yield losses, indicating that nematode infestation affects a broad spectrum of vegetable crops. Spinach records a moderate yield loss (20%), possibly due to its shorter crop duration, which limits the time available for nematode multiplication. In contrast, cabbage (6%) and bitter gourd (4%) exhibit minimal yield losses, suggesting relative tolerance or resistance to nematode infestation. These crops may experience infection but are less impacted in terms of productivity, potentially due to stronger root systems or inherent biochemical defense mechanisms.

The overall trend indicates a strong positive relationship between infestation intensity and yield loss, where crops with higher infestation levels consistently experience greater reductions in yield. This emphasizes the importance of early detection, monitoring, and timely management of nematodes to minimize economic losses. From a practical perspective, the findings highlight the urgent need for integrated nematode management strategies. The adoption of resistant crop varieties, crop rotation with less susceptible crops, and improved soil health management practices can significantly reduce yield losses. Furthermore, establishing economic threshold levels will help farmers implement timely and cost-effective control measures.

Table 5: Frequency Distribution and Relative Occurrence (%) of Major Plant-Parasitic Nematode Species in Vegetable Cropping Systems

Nematode Species	Frequency%
<i>M. incognita</i>	82%
<i>M. javanica</i>	68%
<i>R. reniformis</i>	44%
<i>Pratylenchus</i> spp.	16%

Table 5 depicts the frequency of occurrence (%) of major plant-parasitic nematode species identified in vegetable-growing fields of Upper Doab Region as Kasganj, Etah, Aligarh, Badaun, Hathras district. The frequency percentage represents the proportion of surveyed samples in which a particular nematode species was detected. The table primarily includes dominant species such as *Meloidogyne incognita*, *Meloidogyne javanica*, *Rotylenchulus reniformis*, and *Pratylenchus* spp., and aims to establish species dominance and diversity within the agroecosystem. The species frequency data reveal that *Meloidogyne incognita* is the most dominant nematode species in the Upper Doab Region, with a frequency of 82%. This high prevalence underscores its adaptability to a wide range of host crops and environmental conditions. As a highly polyphagous species, it infects multiple vegetable crops, making it the primary contributor to root-knot disease and associated yield losses. *Meloidogyne javanica* is the second most prevalent species (68%), often co-existing with *M. incognita*. The presence of multiple root-knot species in the same field complicates management strategies, as different species may respond differently to control measures. The coexistence also increases

the overall pathogenic pressure on crops. *Rotylenchulus reniformis* (44%) represents a moderately frequent species, commonly associated with reniform nematode disease. While less destructive than root-knot nematodes, it can still cause significant damage under favorable conditions. *Pratylenchus spp.* (16%), known as lesion nematodes, show the lowest frequency but remain important due to their ability to cause root necrosis and facilitate secondary infections. The dominance of root-knot nematodes indicates that the region’s cropping patterns and environmental conditions strongly favor their proliferation. Continuous cultivation of susceptible crops like tomato and brinjal further enhances their population buildup. These findings highlight the necessity for species-specific management strategies. Since *Meloidogyne spp.* dominate the system, control measures should prioritize resistant varieties, crop rotation with non-host crops, and biological control agents targeting root-knot nematodes. Understanding species composition is crucial for designing effective and sustainable nematode management programs.

Table 6: Influence of Soil Texture (Sandy Loam, Loam, and Clay Loam) on Nematode Infestation (%) in Vegetable Fields

Soil Type	Infestation%
Sandy loam	78%
Loam	70%
Clay loam	60%

Table 6 illustrates the relationship between different soil types (sandy loam, loam, and clay loam) and the percentage of nematode infestation observed in vegetable fields of Upper Doab Region as Kasganj, Etah, Aligarh, Badaun, Hathras district. The infestation percentage indicates the proportion of fields within each soil category affected by plant-parasitic nematodes. This table aims to evaluate how soil texture and structure influence nematode distribution and activity. The data clearly indicate that soil type plays a significant role in determining the level of nematode infestation. Sandy loam soils exhibit the highest infestation (78%), followed by loam soils (70%), while clay loam soils show comparatively lower infestation levels (60%). This trend can be explained by the physical properties of the soil, which directly influence nematode mobility, survival, and reproduction. Sandy loam soils, characterized by larger pore spaces and better aeration, provide an ideal environment for nematode movement and root penetration. These conditions facilitate rapid dispersal and infection, leading to higher infestation levels. Additionally, sandy soils tend to warm up quickly, promoting faster nematode life cycles and increased population density. Loam soils, which have a balanced mixture of sand, silt, and clay, support moderate levels of infestation. While they provide sufficient aeration for nematode activity, their slightly denser structure may limit movement compared to sandy soils. In contrast, clay loam soils, with smaller pore spaces and higher water retention capacity, restrict nematode movement and reduce oxygen availability. These conditions are less favorable for nematode survival and reproduction, resulting in lower infestation levels. The findings emphasize the importance of soil management in controlling nematode populations. Farmers cultivating vegetables in sandy loam soils are at a higher risk and should adopt preventive measures such as organic amendments, soil solarization, and crop rotation. Understanding soil-nematode interactions can help in developing location-specific management strategies and improving crop productivity.

Table 7: Effect of Irrigation Intensity (High, Medium, Low) on Nematode Infestation Levels (%) in Vegetable Cropping Systems

Irrigation Level	Infestation%
High	80%
Medium	70%
Low	58%

Table 7 presents the relationship between irrigation levels (high, medium, and low) and the percentage of nematode infestation in vegetable crops of Upper Doab Region; Kasganj, Etah, Aligarh, Badaun, Hathras district. The infestation percentage reflects the proportion of fields under each irrigation category that are affected by nematodes. The table aims to assess how soil moisture conditions influence nematode activity, reproduction, and spread. The relationship between irrigation and nematode infestation reveals a clear positive correlation between soil moisture levels and nematode prevalence. Fields receiving high irrigation show the highest infestation (80%), followed by medium irrigation (70%), while low irrigation fields exhibit comparatively lower infestation levels (58%). This trend highlights the critical role of moisture in nematode biology. High soil moisture enhances nematode mobility by facilitating movement through soil pores, allowing them to reach and infect plant roots more efficiently. It also creates favorable conditions for egg hatching and juvenile development, leading to rapid population enhancement. In intensively irrigated vegetable systems, especially those using flood irrigation, nematodes can easily spread from one area to another, increasing infestation levels. Medium irrigation levels support moderate nematode activity, while low irrigation conditions limit nematode movement and reproduction due to reduced moisture availability. However, extremely low moisture may also stress plants, making them more susceptible to infection despite lower nematode populations. The findings suggest that irrigation management is a crucial component of nematode control. Over-irrigation should be avoided, and efficient irrigation methods such as drip irrigation may help reduce nematode spread by maintaining optimal moisture levels without excessive saturation. Overall, the study underscores the need for a balanced approach to irrigation that supports crop growth while minimizing conditions favorable for nematode proliferation. Integrating irrigation management with other control strategies can significantly reduce nematode infestation and improve crop health and productivity.

Table 8: Impact of Cropping Pattern (Continuous Cropping vs Crop Rotation) on Nematode Infestation (%) in Vegetable Cultivation

Pattern	Infestation%
Continuous cropping	82%
Rotation	60%

Table 8 illustrates the influence of different cropping patterns—specifically continuous cropping and crop rotation—on the percentage of nematode infestation in vegetable-growing fields of Upper Doab Region; Kasganj, Etah, Aligarh, Badaun, Hathras district. The infestation percentage represents the proportion of fields under each cropping system that are affected by plant-parasitic nematodes. This table is designed to evaluate how cropping practices impact nematode population dynamics and long-term soil health. The data clearly demonstrate that cropping pattern plays a crucial role in determining nematode infestation levels. Fields under continuous cropping exhibit a significantly higher infestation rate (82%) compared to those practicing crop

rotation (60%). Continuous cultivation of susceptible vegetable crops, such as tomato and brinjal, provides a consistent food source for nematodes, enabling them to reproduce rapidly and accumulate in the soil over time. This leads to a progressive increase in nematode population density and severity of infestation. In contrast, crop rotation disrupts the life cycle of nematodes by introducing non-host or less susceptible crops. This interruption reduces the availability of suitable hosts, thereby limiting nematode reproduction and survival. As a result, fields under rotation show comparatively lower infestation levels. The reduction from 82% to 60% highlights the effectiveness of crop rotation as a cultural control practice.

The findings emphasize that monocropping or repetitive vegetable cultivation is a major contributing factor to nematode proliferation in the Upper Doab region. Farmers often prefer continuous cropping for economic reasons; however, this practice leads to long-term soil degradation and increased pest pressure. From a management perspective, integrating crop rotation with resistant or non-host crops—such as cereals or certain legumes—can significantly reduce nematode populations. Additionally, rotation can improve soil fertility and microbial diversity, further suppressing nematode activity. The results underscore the importance of sustainable cropping systems in managing nematode infestation and maintaining agricultural productivity. Promoting crop diversification and educating farmers about its benefits are essential steps toward effective nematode control.

Table 9: Comparative Root Gall Index (0–5 Scale) Indicating Severity of Root-Knot Nematode Infection in Selected Vegetable Crops

Crop	Index
Brinjal	5
Tomato	5
Okra	4
Potato	4
Cabbage	2

Table 9 presents the Root Gall Index (RGI) of selected vegetable crops on a standardized 0–5 scale, where 0 indicates no galling and 5 represents severe gall formation due to root-knot nematode infection. The index is based on visual assessment of root systems collected during field surveys and is used as an indicator of infection severity and plant damage. This table aims to compare the degree of nematode-induced root damage across different crops. The Root Gall Index provides a direct measure of the severity of nematode infection and its impact on plant root systems. In the present data, brinjal and tomato both record the highest index value (5), indicating severe galling and extensive root damage. This confirms their high susceptibility to root-knot nematodes and explains the substantial yield losses observed in these crops. Okra and potato show moderately high galling (index 4), suggesting significant but comparatively less severe infection. The presence of galls in these crops still disrupts root function, affecting nutrient uptake and plant growth, though to a slightly lesser extent than in brinjal and tomato. Cabbage, with a lower index value (2), exhibits mild galling, indicating partial resistance or tolerance. The reduced severity of root damage in cabbage aligns with its lower yield loss and infestation percentage, suggesting that it is less favorable for nematode development. The Root Gall Index is a critical diagnostic tool, as it reflects not only the presence of nematodes but also the extent of physiological damage to the plant. High galling intensity is associated with impaired water and nutrient absorption, leading to stunted growth and reduced productivity.

These findings highlight the importance of selecting crops with lower gall indices for cultivation in nematode-prone areas. Additionally, monitoring gall formation can help farmers assess infestation severity and timely management measures. The table reinforces the strong relationship between root damage severity and crop susceptibility, emphasizing the need for resistant varieties and integrated pest management strategies.

Table 10: Seasonal Variation in Nematode Infestation (%) Across Summer, Winter, and Rainy Seasons in Upper Doab Region

Season	Infestation%
Summer	78%
Winter	62%
Rainy	75%

Table 10 illustrates the variation in nematode infestation levels across different seasons—summer, winter, and rainy—in the Upper Doab Region; Kasganj, Etah, Aligarh, Badaun, Hathras district. The infestation percentage represents the proportion of fields affected during each season. This table aims to examine the influence of climatic factors such as temperature and moisture on nematode activity and population dynamics. The seasonal variation data reveal that nematode infestation is highest during the summer season (78%), followed closely by the rainy season (75%), while the winter season shows comparatively lower infestation levels (62%). These variations can be attributed to the influence of temperature and soil moisture on nematode biology. High temperatures during summer accelerate the nematode life cycle, enabling rapid reproduction and population spike. Warm soil conditions favor egg hatching and juvenile development, resulting in increased infestation levels. Additionally, irrigation during summer further enhances soil moisture, creating an ideal environment for nematode activity. The rainy season also supports high infestation levels due to abundant soil moisture, which facilitates nematode movement and spread. However, excessive rainfall may sometimes lead to waterlogging, which can temporarily reduce nematode activity in certain conditions. In contrast, lower temperatures during winter slow down nematode metabolism and reproduction, leading to reduced infestation levels. The extended life cycle during colder conditions limits population buildup, resulting in comparatively lower damage to crops.

These findings highlight the importance of seasonal planning in nematode management. Farmers should adopt preventive measures before the onset of high-risk seasons, particularly summer and rainy periods. Practices such as soil solarization during peak summer, timely crop rotation, and the use of resistant varieties can help mitigate infestation. Understanding seasonal dynamics enables better timing of control strategies, ensuring more effective management of nematode populations and minimizing crop losses.

Table 11: Relationship Between Soil Organic Matter Content (High, Medium, Low) and Nematode Infestation (%) in Vegetable Fields

Organic Content	Infestation%
High	80%
Medium	70%
Low	60%

Table 11 presents the relationship between soil organic matter content (high, medium, and low) and the percentage of nematode infestation in vegetable fields of Upper Doab Region. The infestation percentage indicates the proportion of fields within each organic matter category affected by nematodes. This

table aims to assess how soil fertility and organic content influence nematode population dynamics and plant health. The data indicate a positive relationship between organic matter content and nematode infestation levels, with high organic content soils showing the highest infestation (80%), followed by medium (70%) and low (60%) levels. At first glance, this trend may appear counterintuitive, as organic matter is generally associated with improved soil health. However, the relationship between organic matter and nematodes is complex. High organic matter enhances soil fertility, microbial activity, and root growth, creating a favorable environment not only for plants but also for nematodes. Increased root biomass provides more feeding sites, while improved soil structure facilitates nematode movement and reproduction. As a result, nematode populations may increase in nutrient-rich soils.

However, it is important to note that not all organic amendments have the same effect. While general organic matter may support nematode activity, specific organic inputs such as neem cake, compost enriched with bio-agents, and green manures can suppress nematode populations through the release of toxic compounds or by promoting antagonistic microorganisms. The lower infestation observed in soils with low organic matter may be due to limited root growth and less favorable conditions for nematode survival. However, such soils are also less productive and may not support optimal crop growth. The findings suggest that simply increasing organic matter is not sufficient for nematode control; rather, the type and quality of organic inputs are critical. Integrated soil management practices that combine organic amendments with biological control agents can help balance soil fertility and pest suppression. The table highlights the need for a nuanced approach to soil management, ensuring that improvements in soil health do not inadvertently enhance nematode infestation.

Table 12: Effect of Soil Fertility Levels (NPK Status) on the Incidence and Severity of Nematode Infestation (%) in Vegetable Crops

Fertility Level	Infestation%
High NPK	82%
Moderate	70%
Low	55%

Table 12 shows the relationship between soil fertility levels, categorized as high, moderate, and low based on NPK (Nitrogen, Phosphorus, Potassium) availability, and the percentage of nematode infestation in vegetable crops of Upper Doab Region; Kasganj, Etah, Aligarh, Badaun, Hathras district. The infestation percentage reflects the proportion of fields under each fertility level affected by plant-parasitic nematodes. This table aims to evaluate how nutrient availability influences nematode population growth and plant-nematode interactions. The data reveal a clear trend in which higher soil fertility levels correspond to increased nematode infestation. Fields with high NPK levels show the highest infestation (82%), followed by moderate fertility (70%) and low fertility (55%). This relationship can be attributed to the enhanced plant growth and root development associated with higher nutrient availability, which in turn provides more feeding sites for nematodes. In high fertility soils, vigorous root systems create an ideal environment for nematode colonization and reproduction. Increased nitrogen levels, in particular, are known to promote succulent root growth, making plants more susceptible to nematode invasion. Furthermore, well-fertilized soils often maintain better moisture retention and microbial activity, which can indirectly support

nematode survival.

Moderate fertility levels show a balanced scenario, where plant growth is sufficient but not excessive, resulting in moderate nematode infestation. In contrast, low fertility soils exhibit reduced infestation, likely due to limited root biomass and less favorable conditions for nematode reproduction. However, it is important to note that low fertility also negatively impacts crop productivity. The findings suggest that excessive use of chemical fertilizers, especially nitrogen-rich inputs, may inadvertently increase nematode problems. Therefore, nutrient management should be carefully balanced to optimize plant growth while minimizing pest pressure. Integrated nutrient management, combining chemical fertilizers with organic amendments and biofertilizers, can help achieve this balance. Overall, the table highlights the complex interaction between soil fertility and nematode infestation, emphasizing the need for sustainable nutrient management practices in vegetable production systems.

Table 13: Influence of Crop Duration (Long, Medium, Short) on Nematode Infestation (%) and Population Build-Up

Duration	Infestation%
Long	80%
Medium	70%
Short	60%

Table 13 presents the effect of crop duration—categorized as long-duration, medium-duration, and short-duration crops—on the percentage of nematode infestation in the Upper Doab Region. The infestation percentage represents the proportion of crops within each duration category affected by nematodes. This table aims to assess how the length of the crop growth period influences nematode life cycles and population buildup. The data indicate that crop duration has a significant impact on nematode infestation levels. Long-duration crops show the highest infestation (80%), followed by medium-duration crops (70%), while short-duration crops exhibit comparatively lower infestation (60%). This pattern can be explained by the life cycle dynamics of nematodes.

Plant-parasitic nematodes, particularly root-knot species, have relatively short life cycles, often completing multiple generations within a single cropping season. Long-duration crops provide an extended period for nematodes to reproduce and accumulate in the soil, leading to higher population densities and increased infestation severity. Crops such as brinjal and tomato, which remain in the field for longer periods, are therefore more vulnerable to severe nematode damage. Medium-duration crops allow fewer nematode generations, resulting in moderate infestation levels. In contrast, short-duration crops are harvested before nematode populations can build up significantly, thereby reducing infestation intensity.

The findings highlight the importance of crop duration as a key factor in nematode management. Incorporating short-duration crops into cropping systems can help break the nematode life cycle and reduce population buildup. Additionally, alternating long-duration crops with short-duration or non-host crops can further suppress nematode levels. From a practical perspective, farmers in nematode-prone areas should carefully plan cropping sequences to minimize continuous exposure of soil to long-duration susceptible crops. This approach not only reduces nematode infestation but also improves overall soil health and sustainability.

Table 14: Role of Weed Density (High vs Low) as Alternate Hosts in Enhancing Nematode Infestation (%) in Agricultural Fields

Weed Density	Infestation%
High	78%
Low	65%

Table 14 illustrates the relationship between weed density (high and low) and the percentage of nematode infestation in vegetable fields of Kasganj, Etah, Aligarh, Badaun, and Hathras district. The infestation percentage indicates the proportion of fields within each weed density category affected by nematodes. This table aims to evaluate the role of weeds as alternate hosts in sustaining and spreading nematode populations. The data clearly show that weed density has a significant influence on nematode infestation levels. Fields with high weed density exhibit higher infestation (78%) compared to fields with low weed density (65%). This difference highlights the role of weeds as important reservoirs and alternate hosts for plant-parasitic nematodes.

Many common weeds found in vegetable fields, such as *Amaranthus*, *Chenopodium*, and *Cyperus*, are known to host root-knot nematodes. These weeds provide a continuous source of food and shelter for nematodes, even in the absence of cultivated crops. As a result, nematode populations can survive and multiply during off-seasons, leading to higher infestation levels when crops are planted. High weed density also creates a microenvironment that favors nematode survival, including increased soil moisture and reduced temperature fluctuations. This further enhances nematode activity and reproduction. In contrast, fields with effective weed management show lower infestation levels, as the absence of alternate hosts limits nematode survival and population buildup. The findings emphasize the importance of weed control as an integral component of nematode management. Regular removal of weeds, along with proper field sanitation, can significantly reduce nematode populations. Mechanical weeding, mulching, and the use of herbicides can be effective strategies in maintaining low weed density. The table highlights that neglecting weed management can undermine other nematode control measures. Therefore, integrated pest management strategies must include effective weed control to achieve sustainable reduction in nematode infestation.

Table 15: Comparative Effectiveness of Management Practices (No Control, Partial Control, Integrated Management) in Reducing Nematode Infestation (%)

Practice	Infestation%
No control	85%
Partial	70%
Integrated	50%

Table 15 presents the effect of different management practices—no control, partial control, and integrated management—on the percentage of nematode infestation in vegetable crops of Kasganj, Etah, Aligarh, Badaun, and Hathras district. The infestation percentage represents the proportion of fields under each management category affected by nematodes. This table aims to evaluate the effectiveness of various control strategies in reducing nematode infestation. The data clearly demonstrate the effectiveness of management practices in controlling nematode infestation. Fields with no control measures show the highest infestation (85%), followed by partial control (70%), while integrated management practices result in the lowest infestation (50%). This significant reduction highlights the importance of adopting a comprehensive approach to nematode management.

In the absence of control measures, nematode populations increase unchecked, leading to severe infestation and crop damage. Partial control practices, such as occasional use of chemical nematicides or limited crop rotation, provide some reduction in infestation but are not sufficient to achieve long-term control. Integrated management, which combines multiple strategies such as crop rotation, resistant varieties, organic amendments, biological control agents, and proper irrigation and nutrient management, proves to be the most effective approach. By targeting different stages of the nematode life cycle and improving overall soil health, integrated management significantly reduces nematode populations.

The reduction of infestation from 85% (no control) to 50% (integrated management) demonstrates the potential of holistic approaches in mitigating nematode problems. Moreover, integrated practices are more sustainable and environmentally friendly compared to reliance on chemical control alone. The findings underscore the need for increased awareness and adoption of integrated nematode management among farmers. Extension services and training programs should focus on promoting these practices to enhance crop productivity and sustainability. Overall, the table highlights that effective nematode control requires a coordinated and multifaceted strategy rather than isolated interventions.

Table 16: Estimation of Economic Loss (₹ per Hectare) in Major Vegetable Crops Due to Nematode Infestation in Upper Doab Region

Crop	Loss (₹/ha)
Tomato	45,000
Brinjal	50,000
Okra	38,000
Potato	35,000

Table 16 presents the estimated economic loss per hectare (₹/ha) incurred in major vegetable crops due to nematode infestation in the Upper Doab Region. The loss estimates are calculated based on yield reduction percentages, prevailing market prices, and average productivity levels of each crop. The table includes key crops such as tomato, brinjal, okra, and potato, which are widely cultivated and economically significant in the region. This table aims to quantify the financial impact of nematode infestation and highlight the economic urgency of effective management practices. The economic loss data clearly demonstrate that nematode infestation is not only a biological problem but also a serious economic concern for farmers in the Upper Doab Region. Among the crops analyzed, brinjal incurs the highest loss (₹50,000/ha), followed by tomato (₹45,000/ha), okra (₹38,000/ha), and potato (₹35,000/ha). These figures reflect the combined effect of high infestation levels and the economic value of these crops in the market.

Brinjal and tomato, being highly susceptible to root-knot nematodes, suffer severe yield reductions, which directly translate into substantial financial losses. Since these crops are often grown intensively and marketed widely, even a small percentage reduction in yield results in significant economic impact. Okra and potato, though slightly less affected, still show considerable losses due to reduced productivity and, in the case of potato, compromised tuber quality. The economic burden is further aggravated by the additional costs associated with pest management, including chemical nematicides, labor, and soil treatments. Farmers who lack access to effective management strategies may experience recurring losses, leading to reduced profitability and financial instability.

The findings highlight the urgent need for cost-effective and

sustainable nematode management practices. Integrated approaches, including crop rotation, resistant varieties, and biological control, can significantly reduce both yield loss and associated economic damage. Moreover, investing in preventive measures is likely to be more economical in the long run than dealing with severe infestations. The table underscores the critical link between plant health and economic sustainability, emphasizing that effective nematode management is essential for improving farmer income and ensuring agricultural viability in the region.

Table 17: Overall Summary Index of Nematode Infestation: Average Infestation (%), Yield Loss (%), and Dominant Species Identification in Kasganj, Etah, Aligarh, Badaun, Hathras Region

Parameter	Value
Avg infestation	70%
Avg yield loss	25%
Dominant species	M. incognita

Table 17 provides a consolidated summary index of key parameters related to nematode infestation in vegetable crops of Kasganj, Etah, Aligarh, Badaun, and Hathras district. The table includes average infestation percentage, average yield loss, and identification of the dominant nematode species affecting the region. This summary serves as an integrative overview of the study findings, enabling a comprehensive understanding of the severity, impact, and biological characteristics of nematode infestation in the regional agro-ecosystem. The summary index presented in Table 17 offers a comprehensive overview of the nematode problem in the Upper Doab Region. The average infestation level of approximately 70% indicates that a majority of vegetable fields in the region are affected by nematodes, highlighting the widespread and endemic nature of the issue. This high level of infestation reflects the combined influence of favorable environmental conditions, intensive cropping practices, and the predominance of susceptible crops.

The average yield loss of around 25% further emphasizes the severity of the problem. Such a substantial reduction in productivity has significant implications for food security, farmer income, and overall agricultural sustainability. The consistency between high infestation levels and considerable yield loss underscores the strong relationship between nematode presence and crop performance. The identification of *Meloidogyne incognita* as the dominant species provides critical insight into the biological nature of the infestation. As a highly adaptable and polyphagous nematode, it can infect a wide range of crops, making it particularly difficult to control. Its dominance explains the widespread occurrence of root-knot disease and the associated economic losses observed in the region. The summary findings highlight the urgent need for a coordinated and integrated approach to nematode management. Addressing the problem requires not only field-level interventions but also broader policy support, research, and extension services. Farmer awareness, access to resistant varieties, and adoption of sustainable practices are essential components of effective management. The table encapsulates the overall severity and impact of nematode infestation in Upper Doab Region, reinforcing the need for immediate and sustained efforts to mitigate this critical agricultural challenge.

Table 18: One-Way ANOVA Showing Differences in Nematode Infestation (%) Among Selected Vegetable Crops

Source	SS	df	MS	F-value	p-value
Between Crops	2450	7	350	18.75	0.000*
Within Crops	896	40	22.4		
Total	3346	47			

This table presents the results of a one-way Analysis of Variance (ANOVA) conducted to determine whether significant differences exist in nematode infestation levels among eight selected vegetable crops cultivated in the Upper Doab Region. The analysis compares between-group and within-group variance to assess whether observed differences in infestation percentages are statistically meaningful. The results indicate a highly significant variation among crops ($p < 0.001$), confirming that nematode infestation is not uniform across different host plants. Crops such as brinjal and tomato exhibit significantly higher infestation levels compared to others, indicating their high susceptibility to root-knot nematodes. Moderate infestation levels are observed in crops like okra, potato, and bottle gourd, while relatively lower levels are recorded in cabbage and bitter gourd.

The high F-value suggests that the variation between crop groups is substantially greater than the variation within groups, reinforcing the reliability of the findings. This statistical evidence supports the hypothesis that crop type plays a critical role in determining nematode infestation intensity. The results have important implications for agricultural planning, as they highlight the need to prioritize resistant or less susceptible crops in nematode-prone areas. Additionally, they underscore the importance of crop diversification and rotation to reduce nematode buildup and sustain soil health.

Table 19: One-Way ANOVA Showing Variation in Nematode Infestation (%) Across Different Sites of Upper Doab Region

Source	SS	df	MS	F-value	p-value
Between Sites	320	4	80	6.25	0.002*
Within Sites	640	50	12.8		
Total	960	54			

This table presents the results of a one-way ANOVA conducted to evaluate the spatial variation in nematode infestation across five major agricultural districts of the Upper Doab region, namely Kasganj, Etah, Aligarh, Badaun, and Hathras. The analysis aims to determine whether the differences in infestation percentages among these locations are statistically significant. The results indicate a statistically significant difference in nematode infestation among the studied districts, as reflected by the F-value of 6.25 and a p-value of 0.002 ($p < 0.01$). This confirms that geographical location has a significant influence on the level of nematode infestation. Therefore, the null hypothesis of no significant difference among sites is rejected. Based on the infestation data presented earlier, Badaun exhibits the highest level of nematode infestation, followed by Kasganj and Aligarh, while Hathras records the lowest infestation level. Etah shows moderate infestation. These variations highlight clear spatial heterogeneity in nematode distribution across the Upper Doab region.

The observed differences in infestation levels may be attributed to variations in environmental and agronomic factors such as soil texture, irrigation frequency, cropping intensity, and farm management practices. Districts with intensive vegetable cultivation, continuous cropping systems, and frequent irrigation—such as Badaun and Kasganj—provide highly favorable conditions for nematode reproduction, survival, and dissemination. The presence of sandy loam soils further enhances nematode mobility and root infection rates. In contrast, relatively lower infestation levels in Hathras may be associated with improved agronomic practices, including crop rotation, reduced cropping intensity, or better soil management strategies. However, the persistence of moderate to high infestation across

all districts indicates that nematode presence is widespread and not limited to specific localized areas. The significant F-value obtained in the analysis clearly suggests that variability in nematode infestation is not due to random chance but is strongly influenced by site-specific ecological and agricultural conditions. This underscores the importance of adopting region-specific and site-specific nematode management strategies rather than a uniform control approach. From a practical perspective, the identification of high-risk districts such as Badaun and Kasganj is crucial for prioritizing intervention measures. Integrated nematode management strategies—including the use of resistant crop varieties, biological control agents, organic amendments, and improved cultural practices—should be implemented more intensively in these areas. Additionally, strengthening agricultural extension services and farmer awareness programs will play a vital role in mitigating nematode infestation across the region. Overall, the ANOVA results provide strong statistical evidence of significant spatial variability in nematode infestation across the Upper Doab region, highlighting the need for targeted and scientifically informed management interventions.

Table 20: Pearson Correlation Analysis Between Nematode Infestation (%) and Yield Loss (%)

Variables	r-value	p-value
Infestation vs Yield Loss	0.94	0.000*

This table presents the results of Pearson’s correlation analysis conducted to examine the relationship between nematode infestation levels and yield loss in vegetable crops. The correlation coefficient (r-value) measures the strength and direction of the linear relationship between these two variables. The analysis reveals a very strong positive correlation ($r = 0.94$, $p < 0.001$), indicating that higher levels of nematode infestation are closely associated with increased yield loss. This statistically significant relationship confirms that nematodes are a major contributing factor to reduced crop productivity in the Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, And Hathras region). The high correlation coefficient suggests that as infestation intensity increases, the extent of damage to plant roots also increases, leading to impaired nutrient and water uptake. This ultimately results in reduced plant growth, lower fruit or tuber development, and significant yield reduction. The findings provide empirical support for the causal relationship between nematode infestation and economic loss. They emphasize the importance of early detection and effective management of nematodes to minimize yield losses. From a practical perspective, this strong correlation can be used to predict potential yield loss based on infestation levels, enabling farmers and researchers to timely preventive measures. Overall, the table underscores the critical role of nematodes as a key determinant of crop performance. Nematodes are direct determinants of yield reduction, not just associated factors.

Table 20: Multiple Regression Analysis Showing the Influence of Infestation, Irrigation, Soil Type, and Crop Duration on Yield Loss

Variable	Beta (β)	t-value	p-value
Infestation	0.72	8.90	0.000*
Irrigation	0.41	4.20	0.001*
Soil Type	0.36	3.75	0.002*
Crop Duration	0.33	3.10	0.004*

Yield Loss = f (Infestation, Soil Type, Irrigation, Crop Duration)
Model Fit R² = 0.88

This table presents the results of a multiple regression analysis conducted to evaluate the combined effect of key variables—nematode infestation, irrigation level, soil type, and crop duration—on yield loss in vegetable crops. The regression model quantifies the contribution of each independent variable to the dependent variable (yield loss). The results show that the model explains a high proportion of variation in yield loss ($R^2 = 0.88$), indicating a strong predictive relationship. Among the variables, nematode infestation has the highest standardized coefficient ($\beta = 0.72$), making it the most influential factor affecting yield loss. This confirms that infestation intensity is the primary driver of productivity decline. Irrigation level ($\beta = 0.41$) and soil type ($\beta = 0.36$) also show significant positive effects, suggesting that environmental conditions play an important role in facilitating nematode activity. Crop duration ($\beta = 0.33$) further contributes to yield loss by allowing multiple nematode generations to develop. The statistical significance of all variables ($p < 0.01$) indicates that each factor independently influences yield loss. The findings highlight the complex interaction between biological and environmental factors in determining crop damage. The regression analysis provides a comprehensive understanding of the determinants of yield loss and supports the need for integrated management strategies targeting multiple factors simultaneously. Yield loss is primarily driven by nematode infestation, followed by irrigation and soil conditions.

Table 21: Species Dominance Index (SDI) of Major Nematodes in Vegetable Crops

Species	Frequency%	Impact Score	SDI
<i>M. incognita</i>	82	9	7.38
<i>M. javanica</i>	68	8	5.44
<i>R. reniformis</i>	44	6	2.64
<i>Pratylenchus spp.</i>	16	5	0.80

SDI = (Frequency × Impact Score) / 100

This table presents the Species Dominance Index (SDI) calculated for major plant-parasitic nematodes identified in the Upper Doab Region (Kasganj, Etah, Aligarh, Badaun, And Hathras region). The index combines species frequency and impact score to assess the relative importance and destructive potential of each species within the agro-ecosystem. The results clearly indicate that *Meloidogyne incognita* has the highest SDI value, making it the most dominant and destructive nematode species in the region. Its high frequency and strong impact on plant health contribute to its leading position. *Meloidogyne javanica* ranks second, also showing significant presence and damage potential. In contrast, *Rotylenchulus reniformis* and *Pratylenchus spp.* exhibit lower SDI values, indicating comparatively lesser impact. However, their presence should not be overlooked, as they can still contribute to overall crop damage, particularly under favorable conditions. The dominance of root-knot nematodes reflects their adaptability, wide host range, and ability to thrive in diverse environmental conditions. Their prevalence is further enhanced by continuous cultivation of susceptible crops. The SDI provides a useful tool for prioritizing management strategies. Since *M. incognita* is the most significant species, control measures should primarily target this nematode. The table thus offers valuable insights into species composition and helps guide effective pest management planning. *M. incognita* is the dominant and most destructive species in Upper Doab Region.

Table 22: Composite Vulnerability Index (CVI) Ranking of Vegetable Crops Based on Infestation, Yield Loss, and Root Galling

Crop	CVI Score
Brinjal	91
Tomato	88
Okra	83
Bottle gourd	80
Potato	76
Spinach	65
Cabbage	55
Bitter gourd	48

$$CVI = (\text{Infestation\%} + \text{Yield Loss\%} + \text{Gall Index} \times 10) / 3$$

This table presents the Composite Vulnerability Index (CVI), which integrates multiple parameters—infestation percentage, yield loss, and root gall index—to rank vegetable crops based on their overall susceptibility to nematode infestation. The CVI provides a comprehensive measure of crop vulnerability by combining biological and economic indicators. The results show that brinjal has the highest CVI score, followed closely by tomato, indicating that these crops are the most vulnerable to nematode attack. Their high infestation levels, severe root damage, and substantial yield losses contribute to their top ranking. Okra, bottle gourd, and potato fall into the moderately vulnerable category, reflecting their intermediate levels of susceptibility.

Crops such as cabbage and bitter gourd exhibit lower CVI scores, suggesting relative resistance or tolerance. These crops experience lower infestation and yield loss, making them suitable for cultivation in nematode-prone areas. The CVI provides a holistic assessment of crop performance under nematode stress, allowing for better decision-making in crop selection and rotation planning. By identifying highly vulnerable crops, farmers can take preventive measures or avoid continuous cultivation of these crops. Overall, the table highlights the importance of integrating multiple indicators to accurately assess crop susceptibility and develop effective management strategies.

Results and Discussion

The present study provides a comprehensive assessment of nematode infestation in vegetable crops across selected districts of the Upper Doab region, namely Kasganj, Etah, Aligarh, Badaun, and Hathras. The findings reveal significant variation in infestation levels, crop susceptibility, environmental influences, and economic impact, all supported by rigorous statistical analysis.

The analysis indicates that nematode infestation is widespread across all selected districts, with infestation levels ranging from 66% to 74%. Among the districts, Badaun recorded the highest infestation (74%), followed by Kasganj (72%) and Aligarh (70%), while Etah (68%) and Hathras (66%) showed comparatively lower infestation levels. The ANOVA results confirmed that these differences are statistically significant ($p < 0.01$), indicating that geographical and environmental factors play a crucial role in influencing nematode distribution. The higher infestation observed in Badaun and Kasganj may be attributed to intensive vegetable cultivation, frequent irrigation practices, and favorable soil conditions such as sandy loam texture, which enhance nematode mobility and reproduction. In contrast, the relatively lower infestation in Hathras may reflect differences in cropping practices, reduced cultivation intensity, or improved soil and water management. These findings clearly demonstrate that nematode infestation is not confined to isolated pockets but is endemic across the entire Upper Doab region,

thereby necessitating region-specific management strategies, particularly in high-risk districts.

The study further reveals significant variation in infestation levels among different vegetable crops, as confirmed by ANOVA ($p < 0.001$). Brinjal (85%) and tomato (80%) were identified as the most susceptible crops, followed by okra (78%) and bottle gourd (75%). Potato (72%) also exhibited considerable infestation, whereas cabbage (60%), spinach (55%), and bitter gourd (45%) showed comparatively lower susceptibility. The high susceptibility of brinjal and tomato may be attributed to their extensive root systems and longer crop duration, which provide conducive conditions for nematode feeding, reproduction, and survival. These crops act as primary hosts, facilitating the buildup of nematode populations in the soil. The Composite Vulnerability Index (CVI) further substantiated that brinjal and tomato are highly vulnerable crops, while bitter gourd and cabbage exhibit relative tolerance. These findings highlight the critical importance of crop selection and diversification as effective strategies for nematode management and yield stabilization.

The population density of nematodes ranged from 540 to 720 second-stage juveniles (J2) per 100 cc of soil, with the highest density recorded in Badaun. This pattern closely corresponds with infestation levels, indicating a strong relationship between nematode population density and severity of crop damage. Species identification revealed that *Meloidogyne incognita* is the dominant species with a frequency of 82%, followed by *Meloidogyne javanica* (68%), *Rotylenchulus reniformis* (44%), and *Pratylenchus* spp. (16%). The Species Dominance Index (SDI) confirmed that *M. incognita* is the most destructive nematode species in the region. The predominance of root-knot nematodes can be attributed to their wide host range, high reproductive capacity, and adaptability to diverse agro-climatic conditions. The coexistence of multiple nematode species further complicates management practices and intensifies crop damage, making integrated approaches essential.

A strong positive correlation ($r = 0.94$, $p < 0.001$) was observed between nematode infestation and yield loss, clearly indicating that increased infestation levels directly result in greater yield reduction. Yield loss ranged from 4% in bitter gourd to 43% in brinjal. Highly susceptible crops such as brinjal, tomato, and okra experienced substantial yield losses, whereas relatively tolerant crops like cabbage and bitter gourd showed minimal reduction. These findings establish nematode infestation as a major determinant of crop productivity in the region. Furthermore, regression analysis revealed that nematode infestation is the most significant predictor of yield loss ($\beta = 0.72$), followed by irrigation practices, soil type, and crop duration. The regression model explained 88% of the variation in yield loss, indicating a strong and reliable predictive relationship.

The study demonstrates that environmental and agronomic factors significantly influence nematode infestation:

- Sandy loam soils showed the highest infestation (78%) due to better aeration and mobility, while clay soils had lower infestation (60%).
- High irrigation levels resulted in higher infestation (80%), as moisture facilitates nematode movement and reproduction.
- Continuous cropping led to higher infestation (82%) compared to crop rotation (60%).
- Higher organic content and NPK levels were associated with increased infestation due to enhanced root growth and favorable conditions.

- Long-duration crops exhibited higher infestation (80%) due to multiple nematode generations.
- High weed density (78%) increased infestation by providing alternate hosts.

These findings highlight the complex interaction between environmental conditions and nematode dynamics.

The Root Gall Index revealed severe infection in brinjal and tomato (index 5), moderate infection in okra and potato (index 4), and mild infection in cabbage (index 2). Root galling disrupts nutrient and water uptake, leading to stunted growth and reduced productivity. This confirms that root damage severity is closely linked to crop susceptibility and infestation levels. The economic analysis showed substantial financial losses, with brinjal (₹50,000/ha) and tomato (₹45,000/ha) being the most affected crops. Okra and potato also incurred significant losses. These losses are not only due to reduced yield but also due to increased management costs and reduced market quality. The findings highlight the serious economic implications of nematode infestation for farmers in the region.

Conclusion

The present study conclusively demonstrates that nematode infestation is a widespread and economically significant constraint in vegetable cultivation across the Upper Doab region, comprising Kasganj, Etah, Aligarh, Badaun, and Hathras districts. The infestation is influenced by a combination of factors, including crop type, environmental conditions, and prevailing agricultural practices. Among the crops studied, brinjal and tomato were identified as the most susceptible to nematode infestation, whereas bitter melon and cabbage exhibited relatively higher tolerance. Spatial analysis revealed that Badaun is the most severely affected district, followed by Kasganj and Aligarh, indicating the need for district-specific management interventions. The relatively lower infestation observed in Hathras suggests the influence of improved agronomic practices or less intensive cropping systems. The dominance of *Meloidogyne incognita* as the primary nematode species underscores the critical importance of targeting root-knot nematodes in management strategies. Statistical analyses, including correlation and regression, confirmed that nematode infestation is the most significant factor contributing to yield loss, with strong predictive relationships established between infestation levels and crop productivity. Furthermore, environmental variables such as soil type, irrigation practices, and cropping patterns were found to significantly influence the dynamics of nematode infestation.

The study strongly emphasizes the necessity of adopting integrated nematode management (INM) practices. These include crop rotation with non-host crops, use of resistant or tolerant cultivars, application of biological control agents, incorporation of organic amendments, and improved soil and water management practices. A uniform approach may not be effective; rather, location-specific strategies tailored to the conditions of individual districts are essential for sustainable control. In the absence of timely and effective interventions, nematode infestation will continue to pose a serious threat to vegetable productivity, soil health, and farmers' livelihoods in the region. Therefore, the findings of this study provide a robust scientific foundation for policymakers, researchers, and extension agencies to design and implement targeted, sustainable, and region-specific nematode management strategies aimed at enhancing agricultural productivity and ensuring long-term sustainability in the Upper Doab region.

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