AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 02, Issue: 11 (November, 2025)
Available online at http://www.agrimagazine.in

Climatic Factors and Epidemiological Dynamics of Cereal Cyst Nematode (*Heterodera avenae*) in Indian Cereal Cropping Systems

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Cereal cyst nematode (CCN; *Heterodera avenae*), commonly known as Molya disease, is a persistent soil-borne threat to wheat and barley cultivation in India. The pest has become a major constraint to national food security, particularly in the north-western cereal belt. Economic assessments indicate that avoidable losses in wheat alone reach approximately ₹ 8,967.52 million across Rajasthan and Haryana (Kumar et al., 2020). Rising soil temperatures, erratic rainfall, and shifting moisture regimes associated with climate change are altering the nematode's epidemiology. Warmer winters can shorten diapause and accelerate juvenile emergence, increasing early-season root infection (Baklawa et al., 2017). Similarly, fluctuating soil moisture affects hatching, mobility, and survival of infective second-stage juveniles (J_2), allowing the pest to extend its range into regions once considered marginal. This review synthesizes current understanding of how climatic variables interact with the life cycle of *H. avenae* and outlines adaptive, climate-smart management approaches—such as resistant cultivars, crop rotation, and soil-health-based cultural practices—to safeguard cereal productivity and ensure long-term food security.

Keywords: *Heterodera avenae*, Cereal Cyst Nematode, Molya disease, Climate change, Nematode epidemiology, Integrated Pest Management, Diapause

Introduction

India's agriculture is increasingly shaped by climate-related stress, which amplifies existing pest and disease pressures. Among soil-borne nematodes, the cereal cyst nematode (*Heterodera avenae*) has emerged as one of the most damaging parasites of rabi cereals—particularly wheat and barley. Once confined mainly to the light-textured sandy soils of Rajasthan and Haryana, the pest's distribution has widened in recent decades, with confirmed records from Jammu and Kashmir, Punjab, Delhi, Himachal Pradesh, Uttar Pradesh, and Madhya Pradesh (Duggal et al., 2025).The economic burden is substantial. Plant-parasitic nematodes collectively account for an estimated ₹ 102,039.79 million in annual crop losses across India, and within this total, Molya disease ranks among the most significant. Losses in wheat attributable specifically to *H. avenae* have been estimated at about ₹ 8,967.52 million in Rajasthan and Haryana alone (Kumar et al., 2020). Yield reductions typically range from 15 to over 50 percent, depending on nematode density, soil type, and prevailing environmental conditions. With gradual changes in temperature and precipitation patterns, the epidemiology of *H. avenae* is undergoing notable shifts. Higher winter temperatures can disturb the nematode's dormancy (diapause), while unpredictable soil moisture can influence cyst hatching and juvenile migration. Understanding these interactions is critical for forecasting disease outbreaks and developing integrated, climate-resilient management options. This article reviews the biology and life cycle of *H. avenae*, explores the influence of climatic factors on its development and spread, and highlights practical measures for its management in cereal-based cropping systems under changing environmental scenarios.

Etiology, Symptomology, and Life Cycle of *Heterodera avenae*

Etiology and Disease Overview

Molya disease of cereals is caused by the cyst-forming nematode *Heterodera avenae* Wollenweber, a sedentary endoparasite that attacks the root system of wheat, barley, and related grasses. The nematode survives in soil in the form of brown cysts—hard, lemon-shaped bodies that are actually the dead females encasing hundreds of eggs. These cysts act as the primary source of inoculum and can remain viable in dry soil for several years, even in the absence of a host crop.

Symptoms on Host Plants

The damage caused by ***H. avenae*** is primarily root-based, making infection signs cryptic underground while above-ground symptoms are often mistaken for nutrient or water deficiencies.

- Above-Ground Symptoms: Field appearance is characterized by irregular, patchy areas of severely stunted plants displaying generalized chlorosis (yellowing), often confused with simple nutrient deficiencies or water stress. Tillering is drastically reduced, leading to poor ear formation.
- Below-Ground Symptoms: Invasion points force the host root to branch excessively, creating characteristic, dense clusters of weakened roots, often referred to as "bushy knots."
- Definitive Diagnosis: The clearest sign is the presence of the female body. As the female matures, her posterior swells and bursts through the root cortex, where she is fertilized. After death, her cuticle hardens into a tough, protective, sclerotized, lemon-shaped cyst (dark brown). These cysts shelter hundreds of eggs, allowing the pest to survive for years (diapause) until a new susceptible host is sown.

Life Cycle and Host–Parasite Relationship

The life cycle of *H. avenae* comprises egg, four juvenile stages (J1–J4), and the adult. The first-stage juvenile (J1) develops within the egg and molts once to form the second-stage juvenile (J_2), which is the infective stage. Upon the onset of favorable moisture and temperature, J_2 larvae hatch from the cyst and actively migrate through soil water films toward host roots, guided by chemical cues released from root exudates. After penetration near the root tip, J_2s move intracellularly and establish a permanent feeding site known as a syncytium by inducing the fusion of adjacent root cells. The nematodes then become sedentary, undergoing successive molts to reach the adult stage. Females swell and protrude from root tissue, while males regain mobility and fertilize the females externally. Mature females later die and harden into cysts containing hundreds of eggs, completing the annual cycle. The duration of the life cycle depends strongly on temperature and soil moisture. Under optimum conditions of 18–22 °C and adequate moisture, one complete generation is completed within 7–8 weeks. In cooler or drier environments, diapause in eggs or juveniles allows survival until favorable conditions return, synchronizing nematode emergence with the wheat-barley growing season.

Influence of Climatic Variables on CCN Epidemiology

The severity and spread of Molya Disease are highly influenced by environmental conditions. Climate change accelerates its impact, creating conditions more favorable for the nematode.

Temperature-Mediated Development and Diapause

Temperature is the most critical environmental factor influencing cyst nematode biology.

- Hatching Window: The infective J_2s are programmed to emerge and invade roots optimally within a cool, moist temperature window, typically reported between 5°C and 20°C (Baklawa *et al*., 2017)**.**
- Breaking Diapause: The cyst eggs undergo a mandatory period of diapause. Milder, shorter winters driven by warming trends may prematurely break this diapause, accelerating the life cycle (Baklawa *et al*., 2017).

- Infection Intensity: This acceleration means that young, highly vulnerable crops are exposed to an earlier and heavier wave of J_2 invasion, increasing the overall intensity and damage potential within the short cereal growing season.

Role of Soil Moisture in Juvenile Movement and Hatching

Soil moisture is indispensable for the mobility of the infective J_2s and cyst hatching.

- **Migration Factor:** Moderate soil moisture following early winter rains provides the necessary medium for J_2s to actively migrate through the soil matrix toward host roots, maximizing infection pressure.
- **Protection from Extremes:** While excessively dry or waterlogged soil temporarily halts nematode activity, the parasite gains protection once it establishes the syncytium within the root tissue. This endoparasitic habit shields the nematode from sudden and prolonged soil moisture fluctuations caused by erratic rainfall, allowing the infestation to proceed even when the host plant is struggling with drought or water stress.
- **Geographic Expansion:** The disappearance of limiting cold conditions, coupled with favorable intermittent moisture from erratic rainfall, allows the cysts to survive and establish in previously unaffected regions, directly contributing to the disease's expanding geographic range across the Indo-Gangetic plains.

Socio-Economic and Food Security Implications

The compounded stress of climate change and Molya disease poses a systemic risk to the sustainability of India's dryland cereal production.

- Vulnerability of Marginal Farmers: Small and marginal farmers, who constitute a large percentage of India's agricultural base, are the most vulnerable. Resource limitations often preclude expensive soil testing, nematicide use, or access to new technologies, leaving them reliant on traditional methods that are becoming ineffective under changing climates.
- Underestimated Loss: Because early symptoms mimic nutrient or water stress, losses are frequently misdiagnosed and underestimated. By the time characteristic patches appear, the damage is already severe and irreversible, contributing to chronic, invisible yield losses that threaten farmer livelihoods.
- Threat to National Food Resilience: The potential for widespread yield instability across millions of hectares in the critical wheat belt, fueled by climate-driven expansion, poses a direct challenge to national buffer stocks and long-term food resilience.

Integrated Pest Management (IPM) Strategies for Climate Resilience

Addressing the dynamic threat of Molya Disease requires a scientifically grounded, multi-faceted IPM plan integrated with climate-smart agricultural practices.

Strategy	Rationale and Implementation
Host Plant Resistance	Utilization of resistant or tolerant wheat and barley varieties, such as Raj Molya Rodhak-1, is the most economical and sustainable long-term defense (RARID 2025).
Climate-Smart Crop Planning	Crop Rotation with non-host crops (e.g., pulses, oilseeds like mustard, or potatoes) effectively breaks the nematode's lifecycle and drastically reduces soil inoculum. Adjusting Sowing Dates can help avoid peak periods of J_2 hatching.
Cultural Controls	Deep summer ploughing exposes cysts to solar heat and desiccation during the hot, dry season, significantly reducing viability.
Soil Health Enhancement	Maintaining soil moisture through mulching and incorporating organic matter supports beneficial microbial communities that naturally suppress nematode populations, enhancing the field's natural resilience against parasitic species.
Awareness and Diagnosis	Promoting education among extension workers and farmers is crucial. Regular soil testing and nematode surveys before sowing can provide timely, actionable data for early intervention.

Conclusion

The cereal cyst nematode (*Heterodera avenae*) represents a serious and evolving threat to cereal-based farming systems in India. Climatic shifts—particularly rising winter temperatures and erratic rainfall—are reshaping the nematode's epidemiology, favoring earlier infection and geographic expansion. Sustainable management therefore requires a shift from reactive chemical control to proactive, integrated, and climate-resilient strategies. Emphasis should be placed on resistant varieties, diversified crop rotations, biological control, and improved soil health. Strengthening nematode surveillance and forecasting networks will be critical for protecting wheat and barley productivity, ensuring the resilience of India's food-grain sector under changing environmental conditions.

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