



Reviewed by

Dr. Mayur R. Thesiya
Anand Agricultural University, Anand
Gujarat, India
Email: mayurthesiya2496@gmail.com

***Correspondence**

K.S. Jadon
kuldeep.icar@gmail.com

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Affiliation

¹ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan, India

Current Status and Emerging Trends in Diseases of Cumin (*Cuminum cyminum* L.): Challenges and Management Strategies

K.S. Jadon^{1*}, L.S. Rajput¹, Khushwant B. Choudhary¹, Ritu Mawar¹, R.K. Solanki¹, R.K. Kakani¹

Abstract

Cumin (*Cuminum cyminum* L.) is a high-value seed spice cultivated predominantly in arid and semi-arid regions, with India contributing nearly 70% of global production and trade. Despite its economic and nutraceutical importance, cumin productivity is severely constrained by biotic stresses, particularly diseases such as Fusarium wilt, Alternaria blight, and powdery mildew, whose incidence and severity have increased under intensive cultivation and changing climatic conditions. Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *cumini*, is the most destructive soil-borne disease, leading to chronic field infestation, severe plant mortality, and yield losses exceeding 60–80% in endemic areas. Alternaria blight, primarily caused by *Alternaria burnsii* and *A. alternata*, has emerged as a major foliar disease causing extensive canopy blight, seed discoloration, and quality deterioration, posing serious threats to export standards. Powdery mildew (*Erysiphe polygoni*) further exacerbates yield losses under humid and moderate temperature regimes during flowering and seed development. This review synthesizes current knowledge on the status, distribution, epidemiology, and pathogenic variability of major cumin diseases, with emphasis on recent advances in host resistance, biological control, chemical management, and integrated disease management (IDM). Sustainable disease mitigation requires a holistic IDM approach combining resistant cultivars, crop rotation, organic amendments, biocontrol agents, need-based fungicide use, and improved diagnostics. Continued research on pathogen diversity, resistance breeding, and climate-responsive management strategies is essential for resilient and profitable cumin production systems.

Introduction

Cumin (*Cuminum cyminum* L.) is an annual herbaceous spice crop of the family Apiaceae, cultivated mainly for its dried fruits (“seeds”), which are valued as a condiment and as a raw material for essential oil extraction. It is one of the principal seed spices of arid and

semi-arid regions and plays a significant role in the diet, traditional medicine, and export earnings of producing countries, particularly India and other West–Central Asian nations. The plant is a small, slender annual reaching roughly 20–50 cm, with finely divided leaves and small white-pink flowers borne in compound umbels. The commercial product is the aromatic, elongated, ridged dried fruit, which contains a volatile oil rich in constituents such as cuminaldehyde, terpenes and related phenolic compounds responsible for its characteristic flavor and bioactivity. (Allaq, *et al.*, 2020, Johri, 2011, Agarwal *et al.*, 2017, Meena *et al.*, 2022). Cumin seeds are used whole or ground in curries, spice blends, bakery products, pickles and flavoring formulations, and the essential oil is used in foods, beverages and perfumery. Pharmacological and nutraceutical studies report a wide range of activities including antioxidant, antimicrobial, antifungal, anti-inflammatory, antidiabetic, hepatoprotective, anti-osteoporotic and immunomodulatory effects, which support its use in traditional and modern health products. (Singh *et al.*, 2017, Meena *et al.*, 2022, Allaq *et al.*, 2020, Agarwal *et al.*, 2017). Cumin is believed to have originated in the Eastern Mediterranean to Central/West Asian region, where it has been used for millennia in food and traditional remedies. At present it is widely grown in parts of Asia, North Africa and the Middle East, with major production concentrated in dry, cool winter zones such as those found in India, Iran and neighbouring countries. (Johri, 2011, Agarwal *et al.*, 2017, Allaq *et al.*, 2020, Meena *et al.*, 2022). Cumin is adapted to dry, cool winter climates, performing best on light, well-drained soils under low to moderate humidity, conditions typical of many semi-arid tracts. It is considered an export-oriented, high-value cash crop in countries like India, where it fits well into rabi season rotations and contributes significantly to the income of small land holders and to foreign exchange through seed and spice-oil trade. (Vinod *et al.*, 2022 and Meena *et al.*, 2022; Saranya *et al.*, 2025; Balai *et al.*, 2025; Wadud *et al.*, 2021)

Status

Global cumin cultivation covers roughly 0.8–1.0 million hectares with an estimated world seed production of about 0.9–1.0 million tonnes per year, dominated by

India. India alone contributes around 70% of global cumin output and most of the world trade, with Syria, Iran and Turkey as the other important producers. (CBI 2025, Mehriya *et al.*, 2022). During 2023-24 the major contributors in spice export basket in terms of value were cumin (16%), despite the decline of 11 % in volume, the export value of cumin seed increased by 43% in rupee terms and 39 % in dollar terms of value. (Spice Board, 2024). The cumin-growing area in India is around 5.5 lakh hectares (550,000 ha) mainly concentrated in Rajasthan (about 61% of area) and Gujarat, which together contribute nearly 99% of total cumin production. According to Spices Board India for 2022-23, cumin production is estimated around 435,000 to 555,000 tonnes in India with Rajasthan and Gujarat as leaders.

Major challenges for cumin production

Major challenges for cumin production include biotic stresses like fusarium wilt, alternaria blight, powdery mildew, aphids, and mites; abiotic stresses such as drought, frost, heat, salinity, and temperature fluctuations; and agronomic issues like poor land preparation, broadcasting sowing methods, weed infestation, and labor shortages. Diseases including Fusarium wilt and Alternaria blight cause yield damages, while pests like aphids and thrips damage during flowering. Drought inhibits growth and alters seed biochemistry, frost causes severe injury at flowering and during fruiting, and salinity cuts productivity by up to 55% in salt-sensitive plants. High humidity and unseasonal rain promote powdery mildew and quality loss. (Pagaria and Sharma, 2019; Meena *et al.*, 2024; Meena, 2024; Kumar *et al.*, 2023). Present review focussed on the major diseases of cumin production *viz.*, *Alternaria* blight (caused by *Alternaria* spp. such as *A. alternata*, *A. burnsii*, *A. tenuissima*, and *A. gaisen*), Fusarium wilt (*Fusarium oxysporum* f. sp. *cumini*), and powdery mildew (*Erysiphe polygoni*).

Major Diseases

These diseases (Alternaria blight, Fusarium wilt, and powdery mildew) cause significant yield losses, with Alternaria blight reaching up to 80-98% incidence and 88% severity, Fusarium wilt up to 35-80%, and powdery mildew leading to foliar damage. (Meena *et al.*, 2024; Kumawat *et al.*, 2022; Abdul *et al.*, 2021).

Fusarium Wilt

Fusarium wilt is the most destructive disease of cumin (*Cuminum cyminum* L.), caused mainly by the soil-borne fungus *Fusarium oxysporum* f. sp. *cumini* (Foc), and can lead to very high yield losses, especially under continuous cumin cultivation and favorable environmental conditions. Fusarium wilt causes yellowing, wilting, and plant death from seedling to maturity, with losses up to 35% in Rajasthan and 80% under warm, dry conditions. The pathogen persists in soil and seeds, thriving at 28°C, and no fully resistant genotypes exist, though moderate resistance occurs in lines like UC-220. It is managed through an integrated approach combining resistant cultivars, cultural practices, biological control, and judicious fungicide use. Integrated control uses bioagents like *Trichoderma harzianum*, carbendazim seed treatment, and soil fumigants. (Prajapati *et al.*, 2025; Kumawat *et al.*, 2022; Jagani *et al.*, 2023a; Prasanna and Patel, 2022; Jagani *et al.*, 2023b; Yadav *et al.*, 2023; Dharajiya *et al.*, 2023; Ram and Choudhary, 2023; Özer and Bayraktar, 2015).

Economic importance and distribution

In long-term cumin-growing areas of the Indian arid zone, wilt caused by Foc is consistently identified as the key yield-limiting disease, often forcing farmers to abandon the crop after several years of monoculture. Wilt has been reported from virtually all cumin-growing tracts, with particularly high incidence in fields that have grown cumin continuously for 4–5 years, where stand loss in patches. The build-up of soil inoculum, narrow crop rotations, and increasing commercialization of cumin cultivation has made Fusarium wilt a persistent threat in many production systems. (Jagani *et al.*, 2023b; Yadav *et al.*, 2023).

Etiology and taxonomic status

The causal agent is *Fusarium oxysporum* f. sp. *cumini* Prasad and Patel, a specialized forma specialis within the *F. oxysporum* species complex that shows host specificity to cumin. The pathogen produces septate hyphae, microconidia, macroconidia, and abundant chlamydospores that serve as long-term survival structures in soil; cultures are typically whitish to pinkish with characteristic Fusarium conidial morphology. Pathogenicity tests with multiple isolates have confirmed distinct virulence patterns within Foc,

highlighting pathogenic variability that has direct implications for breeding durable resistance. (Jagani *et al.*, 2023a; Jagani *et al.*, 2023b; Dharajiya *et al.*, 2023; Özer and Bayraktar, 2015; Charan *et al.*, 2023; Talaviya *et al.*, 2018).

Molecular characterization using markers such as ITS and other gene regions has been employed in some recent work to confirm identity and to distinguish Foc from other *F. oxysporum* formae speciales associated with different hosts. However, the forma specialis concept remains largely operational, and there is ongoing interest in refining phylogenetic relationships and population structure within Foc using higher-resolution genomic tools (Dharajiya *et al.*, 2023; Özer and Bayraktar, 2015).

Disease cycle and epidemiology

Foc is a typical soil-borne vascular pathogen whose chlamydospores can persist in soil for several years in the absence of the host, surviving on plant residues or as saprophytes. The primary inoculum resides mostly in the upper 0–5 cm of soil under cumin cultivation, and inoculum levels increase with each year of continuous cumin cropping, showing a strong positive relationship with wilt incidence in the field (Jagani *et al.*, 2023b; Lodha and Mawar, 2014).

Infection usually begins with penetration of the root system, either directly through epidermal cells or via natural openings and wounds, followed by colonization of the cortex and xylem vessels. The pathogen spreads upward through the vascular system, producing abundant microconidia that move with transpiration stream, resulting in blockage of vessels, toxin production, and ultimately plant wilting. Secondary spread within a field occurs via movement of infested soil on irrigation water, farm implements, and contaminated seed lots that carry infested debris, although Foc is primarily soil-borne rather than seed-borne in the strict sense (Özer and Bayraktar, 2015; 2 Jagani *et al.*, 2023; Lodha and Mawar, 2014).

Epidemiological studies indicate that wilt occurrence is strongly influenced by soil moisture, temperature, and cropping history. The disease is favored by relatively warm conditions, typical winter season temperatures in Indian cumin belts, and poorly drained or structure-degraded soils, while certain cultural practices such as deep summer irrigation and organic

amendments can reduce inoculum. High inoculum density, susceptible cultivar, and conducive environment together form the classic disease triangle that leads to rapid early-season plant mortality and further mid-season wilt peaks around flowering (Jagani *et al.*, 2023b; Lodha and Mawar, 2014).

Symptomatology

Wilt symptoms can appear at any crop stage from seedling to maturity, but most severe damage usually occurs when plants are at vegetative or early reproductive stages. Early symptoms include slight chlorosis, epinasty, and drooping of the apical parts, followed by progressive wilting of leaves and stems that may initially be unilateral or confined to a few branches. Infected plants become stunted, with reduced branching and poor seed set, and severely affected plants dry up completely, resulting in characteristic gaps in the field (Yadav *et al.*, 2023; Jagani *et al.*, 2023a; Jagani *et al.*, 2023; Lodha and Mawar, 2014).

On closer examination, affected plants often show dark brown to black discoloration on roots and basal stem, with internal browning of vascular tissues when stems are cut longitudinally. If infection occurs during flowering, umbels may remain sterile or produce shriveled seeds, exacerbating yield loss beyond simple plant mortality. The disease is readily distinguished in the field from foliar blights and powdery mildew by the typical progressive loss of turgor and vascular browning rather than primary leaf lesions or superficial mycelial growth (Özer and Bayraktar, 2015; Jagani *et al.*, 2023a; Jagani *et al.*, 2023b; Lodha and Mawar, 2014).

Pathogenic variability

Studies with collections of *Foc* isolates from different cumin-growing regions have demonstrated considerable variation in colony morphology, growth rate, sporulation, and virulence on standard susceptible cultivars. In experiments where multiple isolates were inoculated at different inoculum levels under pot conditions, isolates differed in the latent period, wilt incidence, and severity, confirming the presence of distinct pathogenic groups (Dharajiya *et al.*, 2023; Talaviya *et al.*, 2018).

Recent work has pointed out that some isolates can cause near-complete mortality of susceptible

genotypes under high inoculum pressure, whereas others produce only moderate wilt under similar conditions. Such variability complicates resistance breeding because genotypes selected against a limited set of isolates may not perform reliably across locations; hence, breeders emphasize multi-isolate, multi-location screening (Dharajiya *et al.*, 2023; Talaviya *et al.*, 2018; Talaviya *et al.*, 2017).

Host range and survival

Foc is regarded as relatively host-specific to cumin, which allows the use of long rotations with non-host crops as a cornerstone of cultural management. However, like other *F. oxysporum* formae speciales, the pathogen can survive saprophytically on crop residues and in association with non-host plants in the rhizosphere, which helps maintain soil inoculum between cumin crops. Survival is mainly through thick-walled chlamydospores that can withstand periods of adverse conditions and remain infective in soil for several years. Population studies in wilt-sick fields have shown that *Foc* propagule density is highest in surface layers and declines with depth and distance from previous cumin rows, supporting practices that disturb this pattern, such as deep ploughing and fallowing with irrigation and organic amendments (Jagani *et al.*, 2023a; Lodha and Mawar, 2014b).

Yield loss and crop damage

Quantitative assessments across different studies indicate that cumulative plant mortality due to wilt can reach 25–40% in typical endemic fields, with many reports of 60–80% yield loss under severe epidemics. In some hot spots where susceptible cultivars are grown continuously and conducive soil conditions prevail, authors have reported near-complete crop failure and up to 100% losses in localized patches. (Prasanna and Patel, 2022; Jagani *et al.*, 2023b; Dharajiya *et al.*, 2023; Özer and Bayraktar, 2015; Yadav *et al.*, 2023; Lodha and Mawar, 2014).

Losses arise not only from the death of plants but also from stunting, reduction in umbels per plant, and poor seed filling in surviving but chronically infected plants. Given cumin's high market value, such yield reductions translate into substantial economic losses at farm and regional scales, making wilt management central to profitable cumin cultivation (Dharajiya *et al.*, 2023; Lodha and Mawar, 2014; Jagani *et al.*, 2023b).

Management: cultural and agronomic measures

Cultural practices are fundamental for managing Foc, especially because the pathogen is soil-borne and difficult to eradicate once established. (Lodha and Mawar, 2014; Jagani *et al.*, 2023b). Recommended strategies include

Crop rotation with non-host crops for several years reduce inoculum densities and wilt incidence, as Foc cannot multiply efficiently in the absence of cumin. Rotations are particularly important in fields with a history of severe wilt and where sowing cumin every year has led to soil “sickness” (Lodha and Mawar, 2014; Jagani *et al.*, 2023b).

Adjusting sowing dates to avoid periods most favorable for infection, and selecting well-drained fields with lighter soils, can lower disease pressure. Fields should be avoided where cumin has been repeatedly grown and where wilt is known to occur heavily (Lodha and Mawar, 2014; Jagani *et al.*, 2023b). Application of organic amendments such as oilcakes and crop residues, followed by summer irrigation or flooding, has been shown to significantly reduce wilt incidence, likely through stimulation of antagonistic microflora and changes in soil physicochemical properties. In particular, incorporation of certain mustard residues or oilcakes in combination with summer irrigation resulted in marked reductions in wilt incidence in field trials (Jagani *et al.*, 2023b).

Studies have reported that balanced fertilization and increased potassium levels can reduce wilt incidence, although specific optimal rates vary with soil and cultivar. Excessive nitrogen, especially in ammoniacal form, may favor disease development, so fertilizer programs should be designed to support plant vigor without predisposing plants to infection (Jagani *et al.*, 2023b).

Removal of diseased plants and destruction of severely infected crop residues, as well as careful cleaning of tools and machinery, help to limit local spread of inoculum within and between fields. (Lodha and Mawar, 2014; Jagani *et al.*, 2023b).

Management: host resistance

Host plant resistance is widely regarded as one of the most sustainable components in managing cumin wilt. Screening programs have evaluated diverse

germplasm and breeding lines under wilt-sick field conditions, identifying lines with partial to high resistance (Prajapati *et al.*, 2025; Talaviya *et al.*, 2017; Prasanna and Patel, 2022; Lodha and Mawar, 2014; Dharajiya *et al.*, 2023; Jadon *et al.*, 2024).

Several studies have identified specific cumin cultivars and lines with reduced wilt incidence. For example: the cultivar GC-4 has been used as a standard check in pathogenicity studies and, in some work, showed tolerance under certain conditions (Dharajiya *et al.*, 2023; Talaviya *et al.*, 2018). Screening of multiple varieties and lines has revealed entries that remained free or nearly free from wilt, such as particular breeding lines that showed no visible symptoms in infested fields (Talaviya *et al.*, 2017; Prasanna and Patel, 2022). Recent research has characterized the resistant cultivar GC-4 (in a different context) as capable of mounting strong biochemical and molecular defenses against Foc, including induction of pathogenesis-related proteins and activation of defense pathways, elucidating mechanisms underlying resistance (Dharajiya *et al.*, 2023). To ensure durability, resistance breeding programs emphasize evaluation across multiple seasons and locations, and against diverse Foc isolates. Resistance is often quantitative and may need to be combined with other management components to give satisfactory field performance (Prajapati *et al.*, 2025; Talaviya *et al.*, 2017; Prasanna and Patel, 2022; Lodha and Mawar, 2014; Dharajiya *et al.*, 2023; Jagani *et al.*, 2023b).

Management: biological control

Biological control has attracted considerable research interest as a more environmentally friendly alternative or complement to chemicals. Several antagonistic fungi and bacteria, as well as arbuscular mycorrhizal fungi, have shown promise against Foc *in vitro* and in field trials (Yadav *et al.*, 2023; Kumar *et al.*, 2016; Lodha and Mawar, 2014; Jagani *et al.*, 2023b; Abo-Elyousr, 2022; Singh and Jadon, 2019).

Trichoderma spp.: Seed treatment and soil application with *Trichoderma harzianum* and related species have significantly reduced wilt incidence in field experiments and often improved plant growth and yield. Some studies reported that Trichoderma-based

treatments reduced wilt more effectively than standard fungicide seed treatments under certain conditions, especially when combined with appropriate cultural practices (Mawar *et al.*, 2019, 2021; Kumar *et al.*, 2016; Bhatnagar *et al.*, 2013; Jagani *et al.*, 2023b).

Bacillus spp. and other bacteria: Recent work identified *Bacillus licheniformis* (CSR-D4) as a strong antagonist, inhibiting Foc mycelial growth by almost 80% *in vitro* and lowering disease incidence in field conditions when applied appropriately. Other bacterial antagonists have also been screened, though their performance can be variable depending on formulation and application method (Yadav *et al.*, 2023; Kumar *et al.*, 2016; Bhatnagar *et al.*, 2013).

Arbuscular mycorrhizal fungi (AMF): Inoculation with AMF species such as *Glomus fasciculatum* and *G. mosseae* reduced wilt incidence and supported plant growth, possibly through improved nutrition and enhanced systemic resistance. Combined applications of AMF with *Trichoderma* and compatible fungicides form part of some integrated packages tested in research trials (Kumar *et al.*, 2016; Jagani *et al.*, 2023b).

Biocontrol agents are generally applied as seed treatments, soil applications, or a combination, and

success often depends on multiple factors including formulation quality, timing, and compatibility with other agronomic and chemical inputs (Kumar *et al.*, 2016; Bhatnagar *et al.*, 2013; Jagani *et al.*, 2023b). Mawar *et al.*., 2019 studies revealed that seed treatment with bio-agents significantly reduced incidence of cumin wilt in all the demonstrations resulting in significant increase in seed yield of cumin.

Management: chemical control

Fungicides remain a widely used tool in managing cumin wilt, especially in high-value commercial production where rapid control is required. The most widely studied fungicides include systemic benzimidazoles and other broad-spectrum products that inhibit Foc growth *in vitro* and reduce disease under field conditions (Ram and Choudhary, 2023; Lodha and Mawar, 2014; Jagani *et al.*, 2023b; Charan *et al.*, 2023).

Seed dressing with carbendazim at appropriate rates per kilogram of seed, often followed by one or more foliar sprays of carbendazim or benomyl, has consistently reduced wilt incidence and improved yield. Combination products such as carbendazim + mancozeb or iprodione + carbendazim have shown strong mycelial growth inhibition *in vitro* and effective

Table 1. List of recent studies based on screening of cumin genotypes for the resistance to wilt

Study focus	Germplasm evaluated	Key outcome	Source
Wilt-sick screening over two seasons	50 cumin germplasms	Identified groups ranging from resistant to highly susceptible under high wilt pressure.	Prajapati <i>et al.</i> , 2025
Germplasm under wilt-sick soil	Multiple local and improved lines	Found several resistant and moderately resistant entries, with susceptible checks showing up to 80% wilt.	Prasanna and Patel, 2022
Variety/line screening	15 varieties/lines	At least one line remained disease-free; others showed varying levels of resistance and susceptibility.	Talaviya <i>et al.</i> , 2017
Landraces for resistance to <i>Fusarium oxysporum</i> f. sp. <i>cumini</i>	64 accessions	Ten accessions, G1, G2, G3, G6, G7, G8, G15, G16, G17, and G49, were highly resistant with low dead plants.	Nouraein <i>et al.</i> , 2020

disease reduction when used as seed treatments (Ram and Choudhary, 2023; Jagani *et al.*, 2023; Charan *et al.*, 2023).

Soil treatment with fumigant or contact fungicides such as sodium N-methyldithiocarbamate (Vapam) has reduced wilt in infested fields, although cost and practical constraints limit large-scale use. Granular formulations of systemic fungicides applied in the root zone after sowing have also been reported to lower wilt incidence and increase plant vigor (Ram and Choudhary, 2023; Jagani *et al.*, 2023b).

Some studies evaluated carbofuran and other granular soil insecticides, reporting reductions in wilt incidence that may be partly related to changes in soil biota and interactions between Foc and plant-parasitic nematodes (Jagani *et al.*, 2023b).

While fungicides can provide strong suppression, overreliance carries risks including cost, potential residue issues, environmental concerns, and the possibility of resistance development in pathogen populations. Consequently, many authors recommend using fungicides as one component of integrated management rather than as a sole strategy (Ram and Choudhary, 2023; Jagani *et al.*, 2023b; Lodha and Mawar, 2014).

Management: botanicals and plant extracts

Botanical extracts are being studied as eco-friendly alternatives or supplements to synthetic fungicides. *In vitro* assays have demonstrated strong antifungal activity of extracts from plants such as *Azadirachta indica*, *Psidium guajava*, *Senna alexandrina*, and *Triumfetta pilosa* against Foc, with certain solvent systems (e.g., acetone or cow-urine-based preparations) giving high levels of mycelial growth inhibition (Jagani *et al.*, 2023a).

These promising laboratory findings suggest potential for field application, but most studies emphasize that further *in vivo* research is needed to confirm efficacy under diverse environmental conditions and to develop practical formulations. Integration of botanicals with biocontrol agents and reduced fungicide doses is a possible future direction in cumin wilt management packages (Jagani *et al.*, 2023a; Jagani *et al.*, 2023b).

Integrated disease management (IDM)

Cumin wilt is best managed through integrated disease

management (IDM), combining host resistance, cultural practices, use of organic amendments, biosolarization, biological control, and carefully targeted chemicals (Ram and Choudhary, 2023; Jagani *et al.*, 2023b; Jadon *et al.*, 2020; Lodha and Mawar, 2014; Bhatnagar *et al.*, 2013; Mawar *et al.*, 2022).

IDM packages includes: use of resistant or at least moderately resistant cultivars suitable for local conditions (Prajapati *et al.*, 2025; Prasanna and Patel, 2022; Jadon *et al.*, 2020; Talaviya *et al.*, 2017; Dharajiya *et al.*, 2023). Crop rotation with non-host crops, avoidance of wilt-sick fields, adjustment of sowing dates, and irrigation to less favourable periods (Jagani *et al.*, 2023b; Lodha and Mawar, 2014). Seed treatment with effective biocontrol agents such as *Trichoderma* spp., sometimes combined with reduced-dose fungicides for enhanced and more stable control (Jadon *et al.*, 2020; Jagani *et al.*, 2023b; Bhatnagar *et al.*, 2013; Kumar *et al.*, 2016). Soil amendments with organic materials and where economically feasible, targeted soil treatment in heavily infested patches (Singh *et al.*, 2012; Jadon *et al.*, 2020; Jagani *et al.*, 2023b). Regular monitoring, rouging of diseased plants, combined with field sanitation and residue management (Israel *et al.*, 2011; Jagani *et al.*, 2023b; Lodha and Mawar, 2014).

Field trials on IDM packages have reported substantial reductions in wilt incidence and significant gains in cumin seed yield compared to untreated controls, demonstrating the practical feasibility of integrated strategies in farmers' fields (Mawar *et al.*, 2019; Ram and Choudhary, 2023; Jagani *et al.*, 2023b; Jadon *et al.*, 2020; Bhatnagar *et al.*, 2013).

Recent advances and research directions

Recent research has focused on understanding the molecular basis of resistance and pathogenicity, as well as refining biological and integrated control methods. For instance, work on the resistant cultivar GC-4 has documented differential expression of defense-related genes and biochemical markers following Foc infection, providing insights that may aid marker-assisted selection. At the same time, new biocontrol strains, including efficient *Bacillus* isolates and improved *Trichoderma* formulations, are being

evaluated for consistency and compatibility in field conditions (Yadav *et al.*, 2023; Dharajiya *et al.*, 2023; Kumar *et al.*, 2016). Advances in pathogen population biology, including molecular typing and possible whole-genome approaches, are expected to clarify the structure and movement of Foc populations and to guide strategies for durable resistance deployment. Continued refinement of IDM packages tailored to specific agro-ecological zones, supported by on-farm validation, remains a priority for making cumin cultivation more resilient to Fusarium wilt pressure (Ram and Choudhary, 2023; Jagani *et al.*, 2023b; Talaviya *et al.*, 2018; Dharajiya *et al.*, 2023; Lodha and Mawar, 2014).

Alternaria blight of cumin

Alternaria blight has emerged as one of the most destructive foliar disease of cumin, capable of causing severe yield and quality losses and threatening export quality standards. (Saranya *et al.*, 2025; Balai *et al.*, 2025; Wadud *et al.*, 2021; Abdel *et al.*, 2021). Alternaria blight, primarily caused by *Alternaria burnsii* and, in some regions, by *Alternaria alternata*. *A. alternata* is the most prevalent and virulent species, with incidence up to 98% in trials across multiple agro-ecological zones, varying by cumin line and location. Alternaria blight exhibits as necrotic spots on leaves, stems, and umbels during flowering and fruiting under high humidity, resulting in shriveled, discolored seeds and up to 80% yield loss worldwide. Management involves resistant lines like CN026 and fungicides such as kresoxim-methyl. (Patel *et al.*, 2025; Abdul *et al.*, 2021). Recent surveys and research indicate that disease prevalence and severity have increased in major cumin-growing regions (Varma *et al.*, 2022; Balai *et al.*, 2025; Saranya *et al.*, 2025).

Distribution of Alternaria blight

Blight symptoms on cumin resembling Alternaria infection were reported several decades ago from major cumin-growing areas of India, and subsequent mycological work established *A. burnsii* as the principal causal agent. Over time, the disease has been documented across Rajasthan, Gujarat, and other Indian states, with high incidence recorded in years with cool, humid weather during reproductive stages. (Saranya *et al.*, 2025; Balai *et al.*, 2025; Varma *et al.*, 2022)

Beyond India, Alternaria blight has been reported from Bangladesh, where *A. alternata* was identified as a major pathogen, and from other cumin-growing countries in West Asia and North Africa. Recent multi-location surveys have documented substantial disease prevalence and yield reductions, indicating a widening geographical footprint likely influenced by changes in climate, intensified cultivation, and movement of infected seed. (Balai *et al.*, 2025; Wadud *et al.*, 2021)

Causal organism(s) and pathogen biology

Alternaria burnsii (Uppal, Kamat & Patel) is widely accepted as the primary etiological agent of cumin blight, with consistent isolation from diseased tissues and fulfillment of Koch's postulates in multiple studies. However, recent work has implicated *A. alternata* as a virulent pathogen of cumin in Bangladesh, and some studies report mixed infections or association of multiple Alternaria morphospecies in diseased samples. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Varma *et al.*, 2022; Makawana *et al.*, 2024)

On common culture media, *A. burnsii* produces dark, fast-growing colonies with abundant conidiation, forming characteristic muriform conidia with transverse and longitudinal septa. Growth rate, colony colour, and sporulation intensity can vary among isolates, but typical conidia are obclavate to ellipsoidal with beak-like extensions, facilitating morphological differentiation from other Alternaria species. (Varma *et al.*, 2022; Varma, and Kumhar, 2023)

Experimental studies show that *A. burnsii* grows over a moderate temperature range with optimum growth and sporulation around mid-temperatures common in winter cumin seasons. Variability in growth response to temperature and pH among isolates has been reported, which may relate to differences in field aggressiveness and adaptation to local environments. (Varma, and Kumhar, 2023; Shekhada *et al.*, 2025)

Molecular diagnostics using internal transcribed spacer (ITS) regions and additional loci have been used to confirm the identity of Alternaria isolates from cumin. Phylogenetic analyses cluster cumin isolates within recognized Alternaria spp., and sequence comparisons have helped distinguish *A. burnsii* from *A. alternata* and related taxa (Wadud *et al.*, 2021; Mali *et al.*, 2017). These findings underscore the need to

consider species and pathotype diversity when designing management strategies and breeding programs. (Balai *et al.*, 2025; Mali *et al.*, 2017; Wadud *et al.*, 2021)

Survival

Alternaria spp. survive between seasons on infected crop residues, in soil, and in or on seed, providing important primary inoculum for subsequent crops. Seed-borne infection is particularly problematic in cumin because infected seed lots facilitate long-distance dissemination and can cause early infection leading to seedling blight and subsequent epidemics. (Balai *et al.*, 2025; Varma *et al.*, 2022; Wadud *et al.*, 2021)

Airborne conidia produced on infected plants and residues serve as the main source of secondary inoculum, enabling rapid disease spread within and between fields under conducive environmental conditions. The presence of alternative hosts and weeds harboring *Alternaria* spp. can also contribute to inoculum build-up and persistence in production landscapes. (Balai *et al.*, 2025; Varma *et al.*, 2022; Wadud *et al.*, 2021)

Symptomatology and disease diagnosis

In the field, *Alternaria* blight typically appears first as small, dark brown to black necrotic spots on leaves, often surrounded by a chlorotic halo, which enlarge and coalesce to form blighted patches. Lesions may develop on petioles and stems, leading to girdling, lodging, and dieback of branches, while infection on umbels results in shrivelling, drying, and poor seed set. (Balai *et al.*, 2025; Varma *et al.*, 2022; Wadud *et al.*, 2021)

Seeds from diseased umbels often appear shriveled, discoloured, and lightweight, with reduced germination and poor market acceptability. Severe epidemics during flowering and seed filling can lead to near-complete canopy blight and substantial yield loss, particularly in susceptible cultivars. (Balai *et al.*, 2025; Varma *et al.*, 2022; Wadud *et al.*, 2021; Abdel *et al.*, 2021)

Symptom confusion with other diseases

Symptom expression can vary with cultivar, environment, and pathogen species or isolate, leading to differences in lesion size, shape, and degree of chlorosis. Superficial similarity to other foliar diseases

such as early infection by powdery mildew or necrotic phases of other pathogens can complicate field diagnosis. (Balai *et al.*, 2025; Wadud *et al.*, 2021)

Differentiating *Alternaria* blight from other leaf spots and blights requires careful observation of lesion characteristics and, ideally, laboratory confirmation through isolation and microscopy. Recognizing typical alternarioid spots with concentric zonation and their distribution on plant parts assists accurate diagnosis. (Balai *et al.*, 2025; Varma *et al.*, 2022)

Standard diagnostic protocols involve surface sterilization of diseased tissue, plating on suitable media, and observing characteristic colony and conidial morphology. Pathogenicity tests using inoculation of healthy seedlings or plants and subsequent re-isolation confirm the causal role of the recovered *Alternaria* isolates. (Varma *et al.*, 2022; Abdel *et al.*, 2021)

For rapid and precise identification, molecular techniques such as PCR amplification and sequencing of ITS regions are used to distinguish between *A. burnsii* and *A. alternata*. *In vitro* fungicide sensitivity assays also a part of diagnostic and management, providing effective information on against field isolates. (Wadud *et al.*, 2021; Varma, and Kumhar, 2023; Mali *et al.*, 2017; Shekhada *et al.*, 2025)

Epidemiology and disease dynamics

Epidemiological studies show that *Alternaria* blight development is strongly influenced by temperature, humidity, and leaf wetness duration. Cool to moderate temperatures, high relative humidity, intermittent rains, and cloudy weather during flowering and early seed development favour infection and disease progress (Balai *et al.*, 2025; Wadud *et al.*, 2021; Varma *et al.*, 2022)

Extended periods of leaf wetness due to dew and irrigation, particularly under dense canopies, promote spore germination and penetration, resulting in rapid lesion expansion and secondary infection cycles. Weather-driven fluctuations in disease intensity between seasons are commonly reported in surveys from major cumin-growing zones. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Varma *et al.*, 2022)

Time-course studies demonstrate a slow initial increase in disease incidence followed by rapid escalation once canopy closure and favourable

microclimate conditions are established, typically from flowering onwards. Disease severity often varies within fields depending on soil moisture, plant density, and airflow, creating gradients from edges or low-lying patches. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Varma *et al.*, 2022)

Late sowing or faulty agronomic practices can align susceptible crop stages with favourable weather, intensifying epidemics. Such comprehensions support recommendations on sowing timings and irrigation management as cultural tools to manage disease risk. (Balai *et al.*, 2025; Makawana *et al.*, 2024; Varma *et al.*, 2022)

Studies on *Alternaria* populations from cumin have revealed considerable variability in cultural traits, sporulation, and pathogenicity among isolates. Some isolates produce larger lesions and cause more rapid blighting, indicating the presence of highly virulent pathotypes within *A. burnsii*. (Mali *et al.*, 2017; Varma *et al.*, 2022)

The identification of *A. alternata* as a pathogenic species on cumin in Bangladesh adds another layer of complexity, as these isolates have shown high aggressiveness under local conditions. Understanding such variability is essential for breeding durable resistance and for designing management strategies that remain effective across diverse pathogen populations. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Mali *et al.*, 2017)

Yield and quality losses

Quantitative assessments indicate that *Alternaria* blight can reduce seed yield substantially, with losses reported up to around 70–80% under severe epidemics in susceptible cultivars. Losses arise from reduced photosynthetic area, premature senescence, poor pollination and seed set, and shrivelling of developing seeds. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Abdel *et al.*, 2021)

Beyond yield, the disease negatively affects seed size, test weight, and essential oil content, leading to downgrading or rejection in export markets with strict quality standards. The economic impact at farm and national levels in major producing countries underscores the importance of effective control measures. (Balai *et al.*, 2025; Wadud *et al.*, 2021; Abdel *et al.*, 2021; Saranya *et al.*, 2025)

Host resistance and breeding programmes

Multiple studies have screened cultivated varieties, breeding lines, and germplasm collections for reaction to *Alternaria* blight using field and controlled-environment trials. Ratings typically classify entries from resistant to highly susceptible based on disease severity indices, with most commercial varieties falling into moderately susceptible to susceptible categories. (Kumawat *et al.*, 2025; Balai *et al.*, 2025)

Some genotypes, including specific lines identified in Bangladesh and India, have shown relatively lower disease severity and are regarded as tolerant or moderately resistant. These entries serve as valuable donors for breeding programs aimed at improving resistance in elite backgrounds. (Kumawat *et al.*, 2025; Balai *et al.*, 2025; Wadud *et al.*, 2021)

Evidence from multi-environment evaluations suggests that resistance to *Alternaria* blight in cumin is quantitative, involving multiple genes and strongly influenced by environmental conditions. Significant genotype × environment interactions have been observed, making stable resistance across locations more difficult to achieve. (Kumawat *et al.*, 2025; Balai *et al.*, 2025)

Breeding efforts are restricted to only screening or evaluation, further constrained by the narrow genetic base of cultivated cumin, small flower size, and partial cross-pollination, all of which complicate hybridization and selection schemes. Nonetheless, recurrent selection and inter-crossing of tolerant lines are being pursued to accumulate favorable alleles. (Balai *et al.*, 2025)

At present, no cumin cultivar is completely immune to *Alternaria* blight, but a few released or advanced breeding lines show partial resistance characterized by slower disease development and reduced final severity. Such cultivars can significantly reduce yield losses when combined with appropriate agronomic and chemical measures. (Balai *et al.*, 2025; Kumawat *et al.*, 2025; Saranya *et al.*, 2025). Future breeding strategies envisage the use of wider germplasm, potential introgression from related species, and deployment of molecular markers once resistance-associated loci are identified. Integration of resistance with other desirable traits such as yield,

quality, and adaptation remains a major research priority. (Balai *et al.*, 2025; Mali *et al.*, 2017; Saranya *et al.*, 2025)

Chemical management

In vitro tests using poisoned food techniques have evaluated a wide array of fungicides against *A. burnsii*, identifying triazoles and strobilurins among the most effective in inhibiting mycelial growth. Active ingredients such as tebuconazole, tebuconazole + trifloxystrobin, propiconazole, azoxystrobin, and combinations involving mancozeb have consistently shown high efficacy in laboratory assays (Sharma *et al.*, 2024; Varma *et al.*, 2023; Shekhada *et al.*, 2025). Furthermore, these results provide a basis for selecting candidate fungicides for field evaluation and for designing effective spray schedules. They also help in understanding potential cross-resistance patterns and the need for rotation among different modes of action. Field trials in major cumin-growing regions have tested single and combination fungicide treatments applied at critical growth stages. Sprays of tebuconazole, mancozeb, chlorothalonil, azoxystrobin, and various premixes have reduced disease severity and significantly increased yield compared with untreated controls, especially when applied prophylactically or at the first appearance of symptoms (Shekhawat *et al.*, 2013; Abdel *et al.*, 2021; Sharma *et al.*, 2024). Optimized spray schedules often involve two to three applications at intervals of about 10–15 days during flowering and early seed filling, balancing cost, efficacy, and residue considerations. Economic analyses indicate favourable benefit–cost ratios for effective fungicide programs when disease pressure is moderate to high. (Shekhawat *et al.*, 2013; Abdel *et al.*, 2021; Sharma *et al.*, 2024)

Excessive reliance on fungicides raises concerns regarding the evolution of fungicide-resistant pathogen populations, environmental contamination, and residues exceeding permissible limits in export markets. Smallholder farmers may face challenges in accessing high-cost fungicides and in adhering to recommended spray intervals and pre-harvest intervals (Shekhada *et al.*, 2025; Saranya *et al.*, 2025; Balai *et al.*, 2025). Therefore, fungicides are best used as part of an integrated disease management strategy, with rotation and mixture of chemistries and emphasis

on need-based applications guided by disease monitoring or forecasting. This approach aims to maintain efficacy while reducing risk of resistance development and minimizing negative externalities. (Shekhada *et al.*, 2025; Saranya, 2025; Kakraliya *et al.*, 2022)

Biological control and botanicals

Biocontrol agents such as *Trichoderma harzianum*, *Trichoderma viride*, and *Pseudomonas fluorescens* have demonstrated antagonistic activity against *A. burnsii* *in vitro* and in some field or pot studies. Mechanisms include competition, mycoparasitism, and production of antifungal metabolites that inhibit pathogen growth and sporulation (Singh and Jadon, 2019; Abdel *et al.*, 2021; Shekhada *et al.*, 2025; Kakraliya *et al.*, 2022). When used as seed treatments or soil and foliar applications, these agents have reduced disease incidence and enhanced plant vigour, sometimes comparable to or synergistic with reduced fungicide doses. Such findings support their inclusion in IDM modules aimed at reducing chemical inputs (Abdel *et al.*, 2021; Kakraliya *et al.*, 2022).

Botanical extracts, particularly neem seed kernel extract and garlic extract have been tested against *Alternaria* blight, showing varying degrees of inhibition *in vitro* and partial control under field conditions. These botanicals can act directly on the pathogen or induce systemic resistance in the host, depending on concentration and application method (Shekhada *et al.*, 2025; Rao *et al.*, 2021; Dhakad *et al.*, 2015). Although their efficacy is generally lower and more variable than synthetic fungicides, botanicals offer eco-friendly options and may be suitable for organic or low-input systems. Practical constraints include standardization of formulations, stability, and frequent application requirements (Rao *et al.*, 2021; Dhakad *et al.*, 2015).

Commercial biopesticide formulations based on *Trichoderma* spp., *Pseudomonas* spp., and neem products are increasingly available and have been incorporated into some field-tested IDM packages. However, adoption remains limited by factors such as inconsistent performance, short shelf life, limited awareness, and cost perceptions among farmers (Dhakad *et al.*, 2015; Kakraliya *et al.*, 2022; Saranya *et al.*, 2025; Balai *et al.*, 2025). Strengthening quality

control, extension services, and farmer training can improve confidence in biopesticides and enhance their role in sustainable management of *Alternaria* blight. Combining biocontrol agents with compatible fungicides and botanicals offers promising avenues for robust and environmentally sound strategies (Dhakad *et al.*, 2015; Kakraliya *et al.*, 2022; Saranya *et al.*, 2025; Balai *et al.*, 2025).

Cultural and agronomic management

Cultural practices that reduce initial inoculum and modify the crop microclimate can significantly influence *Alternaria* blight severity. Crop rotation with non-host species, removal or deep incorporation of infected residues and avoidance of continuous cumin cultivation in the same fields help lower the inoculum load. (Varma *et al.*, 2022; Saranya *et al.*, 2025; Balai *et al.*, 2025)

Sowing at recommended dates to avoid peak conducive weather, maintaining appropriate plant densities, and adopting balanced fertilization and judicious irrigation reduce canopy humidity and disease favourability. Use of disease-free seed and seed treatments with fungicides or hot-water treatments can minimize seedborne infection and early infection foci. (Varma *et al.*, 2022; Balai *et al.*, 2025; Makawana *et al.*, 2024; Abdel *et al.* 2021)

Integrated disease management (IDM) modules

Research has increasingly focused on IDM modules that combine host tolerance, cultural practices, biocontrol agents, botanicals, and rational fungicide use. Such modules may include tolerant cultivars, seed treatment with *Trichoderma* or fungicides, need-based foliar sprays with effective fungicides, and inter-sprays of botanicals or biopesticides (Kakraliya *et al.*, 2022; Abdel *et al.* 2021; Saranya *et al.*, 2025; Balai *et al.*, 2025; Jadon *et al.*, 2020). Field evaluations demonstrate that IDM packages often provide superior disease control, higher yields, and better economic returns compared with single-component approaches while reducing fungicide inputs. These results support policy and extension emphasis on promoting IDM as the cornerstone of *Alternaria* blight management in cumin. (Kakraliya *et al.*, 2022; Abdel *et al.* 2021; Saranya *et al.*, 2025; Balai *et al.*, 2025)

Knowledge gaps and future research needs

Understanding the population structure and

evolutionary dynamics of *Alternaria* species on cumin across regions is still lacking. More detailed studies on host–pathogen interactions, including identification of resistance mechanisms and associated genomic regions, are needed to support marker-assisted selection (Mali *et al.*, 2017; Kumawat *et al.*, 2025; Saranya *et al.*, 2025; Balai *et al.*, 2025; Jadon *et al.*, 2020). Development of disease forecasting models based on weather variables and crop phenology would enable more precise, need-based fungicide applications and improved IDM decision-making. Long-term monitoring of fungicide sensitivity and residue levels is also required to guide sustainable chemical use and compliance with export regulations (Sharma *et al.*, 2024; Saranya *et al.*, 2025; Balai *et al.*, 2025). Advances in genomics, transcriptomics, and microbiome research may open new avenues for innovative management strategies, such as host-induced gene silencing, tailored biocontrol consortia, or discovery of novel resistance sources. Integrating these tools with farmer-centred extension and participatory breeding can enhance adoption and impact (Kumawat *et al.*, 2025; Saranya *et al.*, 2025; Balai *et al.*, 2025). *Alternaria* blight, caused mainly by *A. burnsii* and in some regions by *A. alternata*, has become one of the most serious diseases of cumin, substantially reducing yield and seed quality in major producing countries. Its epidemiology is tightly linked to cool, humid conditions during flowering and seed development and is compounded by seedborne inoculum, pathogen variability, and intensive cultivation practices (Wadud *et al.*, 2021; Abdel *et al.*, 2021; Varma *et al.*, 2022; Balai *et al.*, 2025; Mali *et al.*, 2017). Sustainable management demands an integrated approach combining partial host resistance, improved agronomy, biological and botanical control options, and need-based fungicide use within robust IDM frameworks. Continued research on resistance breeding, pathogen diversity, forecasting tools, and farmer-friendly technologies is essential to mitigate the threat of *Alternaria* blight and safeguard the productivity and export potential of cumin (Saranya *et al.*, 2025; Balai *et al.*, 2025; Kumawat *et al.*, 2025; Kakraliya *et al.*, 2022; Jadon *et al.*, 2020).

Powdery Mildew

Powdery mildew, caused primarily by *Erysiphe*

polygoni DC, emerges as a critical foliar disease in cumin (*Cuminum cyminum* L.), a rabi spice crop vital to India's arid regions like Rajasthan and Gujarat, where it inflicts yield reductions up to 50% through disrupted photosynthesis and seed quality decline. (Meena *et al.*, 2024; Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2025; Meena *et al.*, 2021). Powdery mildew produces white powdery growth on leaves and stems, reducing photosynthesis and seed quality, often co-occurring with blight in humid conditions. It is favoured by cool high humid weather or cloudy weather with high relative humidity, leading to epidemics in major cumin areas (Meena *et al.*, 2024; Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2025; Meena *et al.*, 2021). Cultural practices, sulfur-based fungicides, and sanitation help manage it alongside other aerial diseases. First noted in cumin fields during February-March flowering, the disease aligns with cool, dry conditions favoring spore dispersal, positioning it among key aerial threats alongside wilt and blight. Extensive surveys in North Gujarat report incidence rates of 20-60%, underscoring the need for targeted interventions in cumin production systems (Meena *et al.*, 2024; Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2025; Meena *et al.*, 2021).

Symptoms

Disease onset features discrete white, floury patches on upper leaf surfaces, rapidly coalescing into dense mycelial mats enveloping stems, peduncles, flowers, and maturing seeds. Affected foliage exhibits upward curling, chlorosis, and senescence, culminating in defoliation that exposes fruits to sunscald and secondary pests. Advanced infections stunt plant vigor, shrivel umbels, and diminish seed weight, with powdery growth remaining superficial yet profoundly impairing host physiology unlike tissue-invasive mildews. (Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2025; Meena *et al.*, 2021)

Causal Organism

Erysiphe polygoni DC, an ascomycete in the Erysiphaceae family, functions as an obligate biotrophic parasite, sustaining via haustoria that penetrate epidermal cells without breaching deeper tissues. Hyaline, branched conidiophores bear barrel-shaped conidia in chains, enabling wind-mediated dissemination, while cleistothecia house ascospores

for sexual overwintering. Morphotaxonomic traits include foot-cell morphology and fibrosin bodies, confirming its identity across Apiaceae hosts like cumin (Khunt *et al.*, 2017; Meena *et al.*, 2021).

Etiology and Disease Cycle

Conidia germinate directly on host surfaces within hours under 15-25°C and 95%+ humidity, forming appressoria and haustoria to colonize epidermis. Polycyclic epidemics arise from diurnal peaks in conidial release, with each lesion yielding thousands of spores over 5-7 days, thereby perpetuating spread until canopy senescence. Primary inoculum derives from cleistothecia on debris or collateral hosts, with seed transmission amplifying risks in monocropped systems. (Dange, 1999)

Epidemiology

Optimal proliferation occurs at 20-28°C daytime, >90% night RH, and low wind, peaking post-anthesis in rabi cumin belts amid dew-laden mornings. Dense canopies (>30x10 cm spacing) trap humidity, while excess nitrogen fosters susceptible succulent growth; disease gradients correlate positively with inoculum density and inversely with sunlight. In India, February epidemics coincide with fronts lowering temperatures below 25°C, projecting 30-50% losses sans management (Gojiya *et al.*, 2025; Dange 1999; Meena *et al.*, 2024).

Host-Pathogen Interactions

Pathogen induces host hypersensitive responses minimally, instead reprogramming metabolism for biotrophy, suppressing defenses via effector proteins and eliciting chlorosis via toxin-like metabolites. Cumin's lack of R-genes yields universal susceptibility, though quantitative trait loci underlie partial tolerance in elite lines. Nutrient diversion to fungal biomass curtails seed filling, with proteome shifts revealing downregulated photosynthesis genes (Vielba-Fernández *et al.*, 2020; Patel *et al.*, 2018; Dange, 1999).

Disease Management

Cultural Methods

Timely sowing (mid-October), 30x8-10 cm spacing, and rogueing infected plants enhance ventilation and inoculum dilution. Rotation with graminaceous crops and balanced NPK (60:40:20 kg/ha) curbs residue survival and lush foliage. Sulfur dusting pre-flowering

sanitizes fields economically at 15 kg/ha thrice. (Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2025)

Host Resistance

Screening reveals Gujarat Cumin-4 (GC-4) and RZ-19 as moderately resistant, sustaining <20% PDI versus 50%+ in checks like GC-1. Breeding integrates polygenic tolerance with wilt resistance, though pathogen variability demands continual evaluation. (Dange 1999; Meena *et al.*, 2024; Patel *et al.*, 2018; Dharajiya *et al.*, 2023)

Chemical Control

Hexaconazole 5% SC (0.1%), tebuconazole 25.9% EC (0.1%), and propiconazole 25% EC (0.1%) at 15-day intervals from 10% PDI onset suppress by 70-85%, boosting yields 25-40%. Sulfur 80% WP (0.2%) offers cost-effective alternatives, though rotation mitigates DMI/QoI resistance risks noted globally. (PATEL *et al.*, 2025; Khunt *et al.*, 2017; Vielba-Fernández *et al.*, 2020; Kumawat *et al.*, 2024; Patel *et al.*, 2024)

Biological Control

Trichoderma harzianum (5-10 g/kg seed) and *Pseudomonas fluorescens* (2.5 kg/ha) colonize rhizospheres, inducing systemic resistance and hyperparasitizing mycelia for 40-60% reduction. Neem oil 2% sprays rival synthetics, enhancing yields via antibiosis without residues (Patel *et al.*, 2025; Pasupuleti and Lal, 2024; Prajapati *et al.*, 2025; Deepak *et al.*, 2008).

Integrated Disease Management

Modules blending bio-primed FYM (1 t/ha + *T. harzianum* 40 kg), resistant seeds, and 1-2 fungicide sprays achieve 80% control, aligning with IPM thresholds. Forecasting via temperature-RH models optimizes interventions, sustaining eco-friendly productivity. (Patel *et al.*, 2025; Prajapati *et al.*, 2025; Meena *et al.*, 2024).

Conflict of Interest

The authors declare that they have no conflict of interest.

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