

Alternaria blight of cumin status and management in India: A review

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Abstract

Cumin (*Cuminum cyminum* L.) is one of the oldest and most economically significant seed spices, serving as a vital component of India's spice exports and traditional agriculture. However, its productivity is increasingly constrained by *Alternaria* blight, predominantly caused by *Alternaria burnsii*, which can inflict yield losses of up to 80% in major cumin-growing regions each year. The disease commonly manifests after flowering under conditions of high humidity and moderate temperatures (around 18°C), producing dark brown necrotic lesions on leaves and stems. Affected plants exhibit drooping stem tips and shrivelled seeds with reduced viability, leading to severe yield decline. *Alternaria* blight is primarily seed-borne, facilitating the long distance dissemination of the pathogen, while the fungus also persists saprophytically in soil and crop debris, with conidia capable of surviving for extended periods under warm and dry conditions. Over the past three decades, extensive research has been devoted to understanding its symptomatology, etiology, epidemiology, and predisposing environmental factors. This review consolidates existing knowledge on disease diagnosis, pathogen characterization through morphological and molecular tools, and advances in management practices. Integrated approaches encompassing cultural methods, host-plant resistance, bioagents, botanical formulations, and judicious fungicide use have demonstrated significant potential in mitigating *Alternaria* blight. A holistic Integrated Disease Management (IDM) framework, combining eco-friendly and resilient strategies, holds promise for sustaining cumin productivity and ensuring long-term disease suppression in changing agroclimatic environments.

Keywords: *Alternaria*, etiology, epidemiology, predisposing factors, bio-agents

Introduction

India stands as the world's foremost producer, exporter, and consumer of seed spices, contributing nearly 80–85% of global cumin production and over 70% of international trade (Spices Board of India, 2023). Cumin

(*Cuminum cyminum* L.), a member of the *Apiaceae* (*Umbelliferae*) family, holds immense economic, nutritional, and medicinal significance. The dried seeds of cumin are indispensable to culinary practices across Asia, Europe, Africa, and the Americas, imparting a distinctive flavor and aroma that define several

traditional dishes. Believed to have originated in the Mediterranean and Near Eastern regions, cumin is now widely cultivated in India, Turkey, Syria, Iran, Egypt, Morocco, Uzbekistan, Mexico, Chile, and Pakistan (Kunal *et al.*, 2017; Singh *et al.*, 2021). In India, it is popularly known as Jeera, while globally it carries diverse names such as “Kumin” in German, “Komijn” in Dutch, and “Faux Anis” in French (Didwania, 2019a).

Cumin seeds are not only valued as a spice but also for their therapeutic and nutraceutical properties. They contain significant quantities of essential oils (2.5–4.5%), primarily cuminaldehyde, pinenes, and terpenoids, which confer antioxidant, antimicrobial, carminative, and anti-inflammatory benefits (Deepak *et al.*, 2008; Patel *et al.*, 2017). The seeds are rich in carbohydrates (44–46%), proteins (17–18%), fats (20–22%), and trace minerals such as iron, zinc, and calcium, in addition to vitamin E and flavonoids that enhance their pharmacological potential (Rao *et al.*, 2021a; Rawat *et al.*, 2023). Global demand for cumin oil and seeds is expected to grow at an annual rate of 5.4% during 2023–2028, driven by expanding food, cosmetic, and pharmaceutical applications (FAOSTAT, 2024).

In India, Rajasthan and Gujarat account for nearly 95% of the total cumin acreage, producing about 600,000–700,000 tonnes annually (Spices Board of India, 2023). The crop thrives in the semi-arid to arid agro-climates with well-drained sandy loam soils, making it a major livelihood source for small and marginal farmers. Despite its resilience to drought, cumin is highly vulnerable to several biotic stresses. Among the major diseases *viz.*, wilt (*Fusarium oxysporum* f. sp. *cumini*), *Alternaria* blight (*Alternaria burnsii*) and powdery mildew (*Erysiphe polygoni*), *Alternaria* blight has emerged as one of the most devastating and recurrent threat to cumin productivity (Dange *et al.*, 1992; Sharma *et al.*, 2013; Patel *et al.*, 2022). In epidemic years, the disease can cause yield losses ranging from 40% to 80%, and in severe cases, even total crop failure has been reported (Jat *et al.*, 2019a).

Moreover, the injudicious use of fungicides and continuous monocropping of susceptible cultivars have aggravated the situation, leading to fungicide resistance, residue accumulation, and declining export quality (Varma & Kumhar, 2023). As per the Spices Board data (2024), cumin exports dropped by 12% in volume and 15% in value between 2021–2023 due to quality rejections linked to high pesticide residues (Saranya *et al.* 2025). Consequently, sustainable disease management has become a national priority to ensure both domestic profitability and international market compliance.

This review provides a comprehensive synthesis of three decades of research (1990–2025) on *Alternaria* blight in cumin, encompassing its etiology, epidemiology, symptomatology and integrated management strategies. By critically evaluating advancements in chemical, biological, botanical, and integrated control approaches, this paper aims to identify research gaps and propose future strategies for the sustainable management of *Alternaria* blight, thereby ensuring profitable and eco-friendly cumin cultivation for the arid and semi-arid regions of India.

Extent of damage

Alternaria blight, caused by *Alternaria* spp., is a serious disease that poses a major threat to cumin cultivation, leading to substantial yield and quality losses. The disease was first recorded in India from Gujarat by Uppal *et al.* (1938), marking its initial recognition in the country. It was later detected in Pakistan (Shakir *et al.*, 1995) and subsequently reported from Rajasthan (Joshi, 1995), confirming its wide distribution across the cumin-growing regions of South Asia. *A. burnsii* has since been reported as a major pathogen in arid and semi-arid regions worldwide, demonstrating a wide geographical distribution and severe disease incidence. Significant outbreaks have been recorded in India, Iran, Tajikistan, Uzbekistan, Egypt, Syria, Turkey, Morocco, Chile, Mexico, Bulgaria, and Cyprus (Fig. 1). Studies have confirmed its prevalence and pathogenic

variability across diverse climatic zones, highlighting its adaptability and destructive potential on cumin and related crops (Singh *et al.*, 2022; Ghasemi *et al.*, 2021; El-Kholy *et al.*, 2020; Ozdemir *et al.*, 2019; Abdellaoui *et al.*, 2018; Shomurodov *et al.*, 2017; Romero *et al.*, 2016; Martínez *et al.*, 2015).

Alternaria burnsii remains a major constraint in cumin production, causing significant yield losses in arid and semi-arid regions worldwide. Recent studies report that the disease can lead to 50–80% crop losses under favorable conditions, especially during periods of high humidity and rainfall at the flowering stage (Sharma, 2024; ICAR, 2025). In India, severe outbreaks have been documented in Rajasthan, Gujarat, Haryana, and West Bengal, where average yield losses range between 20% and 70%, depending on climatic conditions and cultivar susceptibility. Field assessments have also shown near-total crop failure in localized outbreaks under conducive weather conditions (Jagani *et al.*, 2023). Internationally, *A. burnsii* has been reported as a destructive pathogen in cumin-growing areas of Egypt,

Iran, Morocco, and Turkey, confirming its expanding global occurrence and destructive potential (Varma, 2024). A comprehensive field survey conducted across the major cumin-growing tracts of Jodhpur, Nagaur, and Jaisalmer districts of Rajasthan revealed that *Alternaria blight* severity ranged from 5% to 60%, with the highest intensity recorded during the flowering and umbel formation stages. The disease incidence was notably aggravated under cool, humid conditions following intermittent winter showers, which favored sporulation and rapid secondary spread of *Alternaria burnsii*. Infected plants exhibited premature drying, shrivelled umbels, and malformed seeds, leading to significant yield and quality deterioration. Furthermore, seeds harvested from severely affected plants were discolored, lightweight, and often unpalatable, reducing their market and export value (Varma & Kumhar, 2024). Similar disease trends have been reported in adjoining cumin belts of Barmer and Bikaner, where *Alternaria blight* epidemics caused yield reductions exceeding 45% during conducive seasons (Meena *et al.*, 2021a).

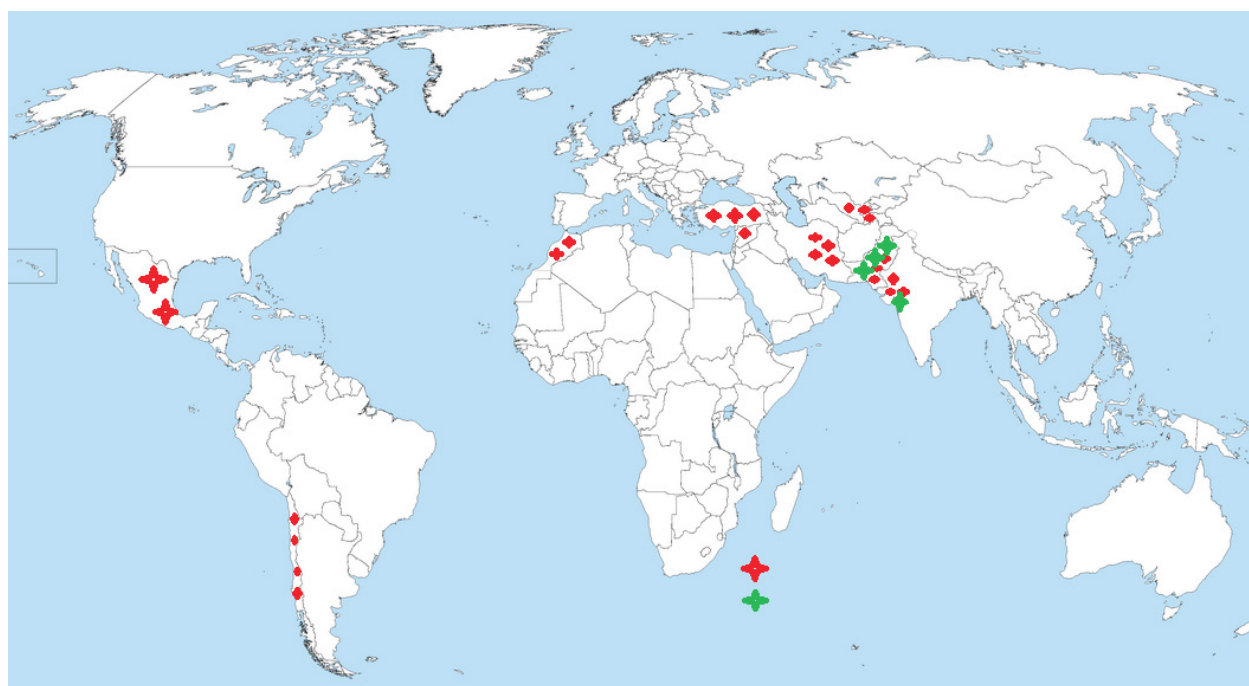


Fig. 1. Worldwide distribution and origin of *Alternaria blight* of cumin

Symptoms

Alternaria blight, caused by *Alternaria burnsii*, affects all aerial parts of the cumin (*Cuminum cyminum* L.) plant, manifesting through diverse and progressive symptoms. The earliest signs appear as small necrotic or chlorotic spots on the tips of tender leaves, which gradually expand, coalesce, and lead to the characteristic blighting of foliage and stems (Chand *et al.*, 2000). As infection advances, irregular brown to black lesions with concentric rings develop on leaves, stems, and inflorescences, giving the crop a scorched appearance (Sharma, 2010). In severe cases, the affected plant parts, especially the leaves and umbels, dry prematurely, resulting in extensive canopy damage and reduced photosynthetic activity (Didwania, 2019a).

The disease tends to intensify under conditions of prolonged humidity, frequent dew deposition, and moderate temperatures (20–25°C), which favor sporulation and secondary infection cycles (Rathod *et al.*, 2019). Infections occurring during the flowering and seed-setting stages are particularly destructive; inflorescences often become dark, shrivelled and brittle, leading to sterile umbels and reduced seed development (Makwana *et al.*, 2024). Seeds formed on diseased plants are typically undersized, discolored, and blackened due to fungal invasion, which compromises both seed viability and market value (Patel *et al.*, 2022). During threshing or winnowing, such light, shrivelled seeds are easily blown away, causing additional quantitative losses (CAZRI, 2024).

Recent pathological studies also report that *A. burnsii* infections can cause partial umbel necrosis and seed abortion, correlating with elevated relative humidity and continuous leaf wetness exceeding 10 hours (Abdel Aziz, 2021).

Etiology of the pathogen

The genus *Alternaria* was first described by Nees von Esenbeck (1816) and later characterized by Berkeley (1836). Among

several pathogenic species, *Alternaria burnsii*, *A. alternata*, *A. tenuissima*, *A. gaisen*, *A. interrupta*, and *A. dumosa* have been implicated as causal agents of cumin blight (Wadud *et al.*, 2021). Taxonomically, the genus *Alternaria* belongs to the kingdom *Fungi*, phylum *Ascomycota*, class *Deuteromycetes* (asexual *Ascomycetes*), subclass *Hyphomycetidae*, order *Moniliales*, and family *Dematiaceae* (Alexopoulos *et al.*, 1996). The fungus produces dark, multicellular asexual spores (conidia), typically measuring 160–200 µm in length, borne singly or in chains on conidiophores with distinct transverse and longitudinal septa. These morphological features, including conidial shape, size, and septation pattern, serve as crucial diagnostic traits for species identification (Pipliya & Jadeja, 2008).

As a necrotrophic pathogen, *Alternaria* infects host tissue by secreting a diverse suite of phytotoxins such as alternariols, altertoxins, tenuazonic acid, and altenuene. These metabolites trigger host cell death either through activation of apoptotic signaling pathways or direct necrotic damage, thereby facilitating rapid colonization (Thomma, 2003; Perrone *et al.*, 2022; Li *et al.*, 2024). Considerable variability has been reported among isolates in terms of cultural growth, pigmentation, sporulation, and pathogenic behavior. A regional survey conducted across Jodhpur, Nagaur, and Jaisalmer districts of Rajasthan revealed wide morphological diversity among *A. burnsii* isolates, with colonies exhibiting differences in color, growth habit, margin pattern, and sporulation density (Fig. 2.1). Microscopic observations confirmed variations in spore length, septation, and beak formation, suggesting intraspecific diversity within local populations (Fig. 2.2).

Recent advances in molecular biology and genomics have transformed the understanding of *Alternaria* taxonomy and species delimitation. Multilocus phylogenetic studies indicate that the genus encompasses more than 300 species, including several cryptic taxa indistinguishable by morphology alone



Fig. 2.1. Pure isolates of *Alternaria burnsii*



Fig. 2.2. Spores of *Alternaria burnsii* under light microscope

(Kusaba *et al.*, 2022). Since the ITS region lacks adequate resolution for species discrimination, molecular markers such as *GAPDH*, *RPB2*, and *TEF-1 α* are now widely adopted for accurate species identification and phylogenetic inference. Studies on *A. burnsii* and *A. alternata* isolates from cumin and related Apiaceous hosts reveal extensive genetic variability, reflecting adaptive evolution and ecological specialization under diverse climatic regimes (Mahapatra *et al.*, 2023).

The production of multiple mycotoxins such as alternariol, alternariol monomethyl ether, altenuene, and tenuazonic acid contributes not only to the pathogenic potential of *Alternaria* species but also raises serious food safety concerns due to their accumulation in stored seeds and spice products (Zheng *et al.*, 2015; Li *et al.*, 2024; Kumar *et al.*, 2023). Genetic polymorphism among *Alternaria* populations has been extensively demonstrated using RAPD, ISSR, and SSR markers, confirming high intraspecific variation across geographical regions and host plants (Kaur *et al.*, 2024).

Interestingly, recent morphological and molecular studies have revealed that certain *Alternaria* species associated with cumin can persist as asymptomatic endophytes, transitioning to pathogenic forms under environmental or physiological stress conditions. This endophytic–pathogenic shift underscores the ecological adaptability and survival strategy of the pathogen in semi-arid ecosystems, complicating disease diagnosis and management (Dutta *et al.*, 2024).

Predisposing factors for disease development

Alternaria species can survive in infected plant debris, soil, and seeds in the form of spores and mycelial fragments, serving as primary sources of inoculum for subsequent cropping seasons. Seed-borne inoculum can initiate infection during germination, causing seedling blight and necrotic lesions on emerging tissues (Khare *et al.*, 2014b). The pathogen remains viable in seed lots for extended periods and under favorable microclimatic conditions can initiate early infection foci (Sharma *et*

al., 2023). The fungus typically thrives and sporulates profusely on crop residues during periods of rainfall, persistent dew, or elevated soil moisture, producing conidia that are easily disseminated by wind, rain splash, or mechanical contact. Upon deposition, conidia germinate and penetrate the host epidermis through natural openings such as stomata or via wounds, establishing infection in young tissues (Khalid *et al.*, 2004; Deshwal, 2004). The disease affects all aerial parts of the cumin plant including stems, leaves, fruits, pods, and umbels and can cause significant yield losses under conducive environmental conditions.

High relative humidity, particularly during the flowering and fruit-setting stages, creates the most favorable conditions for the development of *Alternaria* blight in cumin (Gemawat & Prasad, 1971;). If relative humidity exceeds 90–92%, massive sporulation can occur within 24 hours (Humpherson & Phelps, 1989). Conidia are also capable of surviving under warm and dry conditions for several months, enabling long-distance dispersal and persistence between seasons. Recent epidemiological observations have shown that temperature ranges of 20–30°C combined with prolonged leaf wetness (>10 h) significantly enhance conidial germination and lesion expansion in cumin (*Alternaria burnsii*). Cloudy weather with intermittent rainfall promotes disease onset and accelerates epidemic development by maintaining a favorable microclimate within the crop canopy. Moisture in the form of dew, rainfall, or high atmospheric humidity is essential for successful infection, and at least 9–18 hours of continuous leaf wetness is required for most *Alternaria* species to establish infection (Verma *et al.*, 2025).

Moreover, recent studies have emphasized that nutrient imbalance, particularly high nitrogen and low potassium levels, can predispose plants to infection by altering cuticular thickness and physiological resistance (Rathore *et al.*, 2022). Abiotic stresses such as drought or salinity weaken host tissues, facilitating

pathogen invasion and lesion expansion. Climate variability and increased night-time humidity linked to global warming are now recognized as major contributing factors for the resurgence and expansion of *Alternaria* blight in arid and semi-arid regions (Li *et al.*, 2024). The integration of microclimatic monitoring, seed health testing, and residue management is therefore critical to reduce initial inoculum load and minimize disease outbreaks in cumin-growing areas.

Identification and characterization of *Alternaria* spp.

Identification and characterization of the blight pathogen rely on cultural characterization, morphological, and molecular approaches that improve understanding of its taxonomy and biology, thereby facilitating the development of effective field-level management strategies.

i) Cultural characterization

The mycelial growth and colony characteristics of *Alternaria burnsii* show marked variation across different culture media and environmental conditions, reflecting its adaptability to diverse nutrient compositions. Earlier studies reported that *A. burnsii* exhibited maximum growth and sporulation on Richard's medium (Bhatnagar & Kant, 1994), while isolate AB-01 showed optimal development on potato dextrose agar (PDA) after four to seven days of incubation (Singh *et al.*, 2016a). Similarly, Czapek's Dox Agar has been found to support robust mycelial growth and abundant sporulation (Sawant & Parmar, 2019). Colonies of *A. burnsii* initially appear light to whitish green, gradually turning grey to black with age and display fluffy, irregular, and knot-like radial growth with margins ranging from dirty white to brownish. Recent studies have demonstrated that variations in temperature, pH and media composition significantly influence colony texture, pigmentation, and sporulation intensity, indicating that cultural conditions play a vital role in fungal growth and morphogenesis (Sharma, 2024).

ii. Morphological

The *Alternaria* species infecting cumin exhibit pronounced morphological and cultural variability across isolates. Colony characteristics differ widely in color, texture, and growth rate, while conidial morphology remains an important diagnostic criterion. Microscopic observation revealed conidia that were ellipsoidal to obclavate with both transverse and longitudinal septa. The largest conidial sizes recorded were 88–111 × 26–32 μm (with beak) and 30–38 × 14–18 μm (without beak) in isolate UDP Ab-1, while the smallest sizes (70–88 × 25–32 μm with beak; 31–39 × 15–19 μm without beak) were observed in isolate JLR Ab-1 of *A. burnsii*. In *A. alternata*, the largest conidial dimensions reached 38–48 × 9–11 μm (with beak) and 30–38 × 11–14 μm (without beak) in isolate JSL Aa-2 (Singh *et al.*, 2016b). Conidiophores of *A. burnsii* varied considerably, being branched, straight, geniculate, or irregularly bent, while conidia differed in septation, beak length, and sporulation rate (Varma *et al.*, 2023).

Recent studies corroborate these variations and indicate that morphological plasticity in *Alternaria* spp. is strongly influenced by environmental and nutritional factors, especially light intensity, humidity, and media composition. Scanning electron microscopy and high-resolution imaging have further confirmed subtle distinctions in surface ornamentation, hilum shape, and beak emergence between *A. burnsii* and *A. alternata* isolates.

iii. Molecular

Molecular characterization has become an essential tool for resolving taxonomic ambiguities within the *Alternaria* complex and for understanding pathogen diversity. Earlier investigations based on the internal transcribed spacer (ITS) region grouped *A. burnsii* isolates into two distinct phylogenetic clusters using MEGA 5.6 and DARwin 5 analyses (Singh *et al.*, 2018). Ozer and Bayraktar (2019) developed

species-specific primers enabling rapid and sensitive detection of *A. burnsii* in cumin seeds through both conventional and real-time PCR assays. Sawant and Parmar (2019) also documented high polymorphism (91.51%) among fifteen *A. burnsii* isolates from Gujarat using RAPD markers, highlighting substantial intraspecific variability.

Advancements in next-generation sequencing (NGS) have significantly refined the understanding of *A. burnsii* genetics. The draft genome of *Alternaria burnsii* has been published, providing a valuable resource for comparative genomics and pathogenicity studies (Feng *et al.* 2021). The genome analysis revealed gene clusters associated with secondary metabolite biosynthesis, host-specific toxin production, and effector proteins potentially linked to virulence (Prasanna *et al.*, 2021). Further comparative genomic analyses have shown that *A. burnsii* shares high sequence homology with *A. alternata* and *A. brassicicola*, yet possesses unique gene clusters involved in cutinase activity, oxidative stress tolerance, and conidiation regulation (Dettman *et al.*, 2023; Li *et al.*, 2024). These insights have expanded the molecular basis for differentiation and may explain the adaptability of *A. burnsii* to arid agro-ecosystems.

Recent multilocus sequence typing (MLST) using genes such as GAPDH, RPB2, and TEF1-α has proven more reliable than ITS markers for delineating *Alternaria* species complexes (Zhou *et al.*, 2024). Whole-genome SNP-based studies are now being utilized to examine population structure and evolutionary relationships of *A. burnsii* across cumin-growing regions (Verma *et al.*, 2025).

Management strategies

Since *Alternaria* blight spreads rapidly under favorable environmental conditions, its management largely relies on preventive or prophylactic approaches rather than curative measures (Didwania, 2019b). Effective disease management aims to minimize inoculum

potential, restrict pathogen dissemination, and enhance the crop's physiological resilience. Integrated management strategies combining cultural, biological, and chemical interventions have been developed to reduce disease incidence and sustain cumin productivity. Adoption of these approaches not only mitigates yield losses but also enhances the profitability and sustainability of cumin cultivation in blight-prone regions.

A. Cultural management

Cultural practices continue to serve as the first line of defense in managing *Alternaria* blight of cumin, as they help reduce primary inoculum and create unfavorable conditions for pathogen proliferation. Historically, infected seeds and crop residues have been identified as major sources of inoculum (Patil and Desai, 1971; Gemawat and Prasad, 1972). Early recommendations such as hot water seed treatment at 50°C for 30 minutes (Walker, 1952) remain relevant; however, recent studies have optimized these protocols by integrating thermo-chemical treatments and biopriming with *Trichoderma harzianum* or *Pseudomonas fluorescens*, which significantly enhance seed health and vigor while reducing seed-borne *Alternaria* load (Parmar et al., 2023).

Sanitation measures, including deep ploughing and timely removal or incorporation of crop debris, play a crucial role in minimizing pathogen survival between seasons (Kumar et al., 2020). Crop rotation with non-host crops such as mustard, fenugreek, or cereals for two to three years has been shown to effectively lower soil inoculum density (Goyal et al., 2022). Similarly, early harvesting prevents yield losses caused by late-season disease outbreaks (Sharma et al., 2021).

Microclimate management through wider row spacing, raised-bed planting, and improved drainage reduces leaf wetness duration, thereby limiting conidial germination and spread (Rathore et al., 2023). Maintaining soil fertility and avoiding stress conditions is equally important, as nutrient-deficient or

water-stressed plants exhibit higher disease susceptibility. Recent investigations highlight that balanced nutrient application, particularly adequate potassium and micronutrient supplementation, enhances host defense responses against necrotrophic fungi (Singh et al., 2024a).

The use of certified, disease-free, and vigorously growing seeds, combined with hot water or biocontrol-based seed treatments, remains the most effective prophylactic measure against *Alternaria* blight in cumin (Meena et al., 2021b).

B. Management through botanicals and bio-control agents

In recent years, increasing environmental concerns and the limitations of chemical fungicides have accelerated the shift toward eco-friendly management of *Alternaria* blight in cumin through botanicals and biological control agents. "Green pesticides," encompassing plant-derived compounds such as essential oils, secondary metabolites, and natural extracts, have gained global recognition as effective alternatives to synthetic agrochemicals (Koul et al., 2008; Isman, 2020). These botanicals function as antifungal, antibacterial, and repellent agents, often acting synergistically within complex mixtures (Campos et al., 2019).

Among these, azadirachtin, the active principle of neem (*Azadirachta indica*), has demonstrated potent antifungal activity against *Alternaria burnsii* under *in vitro* conditions (Shekhawat et al., 2013). Extracts from *Aloe vera*, *Calotropis procera*, and *Eucalyptus globulus* at 10% concentration significantly inhibited mycelial growth and spore germination in both laboratory and greenhouse studies (Gangopadhyay et al., 2010). Similarly, *Allium sativum* (garlic) extract has shown remarkable efficacy by reducing disease incidence and improving seed yield under field conditions (Kakraliya et al., 2022). Rhizome extracts from turmeric (*Curcuma longa*) and ginger (*Zingiber officinale*) also suppressed *Alternaria* spp. growth, indicating broad-spectrum antifungal potential (Pipliwal, 2013; Patel et al., 2021).

Biological control agents have emerged as another sustainable pillar of *Alternaria* management. Species of *Trichoderma* have received significant attention due to their antagonistic mechanisms, including mycoparasitism, antibiosis, and induced systemic resistance in host plants (Verma *et al.*, 2023;). *Trichoderma harzianum* has exhibited strong inhibition of *A. burnsii* mycelial growth and has effectively reduced blight incidence when applied as a seed treatment, soil amendment, or foliar spray (Deepak *et al.*, 2008; Kumawat *et al.*, 2021). Other species, such as *T. viride* and *T. hamatum*, have also shown comparable inhibitory effects on *A. alternata* and related pathogens (Ghosh *et al.*, 2002; Monaco *et al.*, 2004; Verma *et al.*, 2022). In addition, the use of *Streptomyces griseoviridis*-based formulations like Mycostop has demonstrated potential in suppressing *Alternaria* diseases under controlled conditions (White *et al.*, 1990; Alghamdi *et al.*, 2020).

Integrating botanicals with biocontrol agents under an integrated disease management (IDM) framework offers a holistic strategy to enhance disease suppression while maintaining ecological balance. Recent studies advocate the combined application of *Trichoderma* spp. with neem or garlic extracts, reporting synergistic effects on disease reduction and plant growth promotion (Rajawat *et al.*, 2021; Pandey *et al.*, 2023).

C. Host plant resistance

Host plant resistance represents the most sustainable, cost-effective, and environmentally benign approach for managing *Alternaria* blight in cumin. Although complete resistance has not yet been identified in *Cuminum cyminum*, considerable progress has been made in screening, characterization, and development of tolerant genotypes under diverse agro-ecological conditions (Edison & Kallapurackal, 1989; Mehra *et al.*, 2002; Singh & Selvan, 2004).

Early evaluations identified cultivars such as RZ-19, UC-198, UC-216, MC-43 and Gujarat Cumin-1 & 2 as moderately resistant, exhibiting

reduced disease severity across multiple locations in Rajasthan and Gujarat (Edison *et al.*, 1991; Sunder, 2005). Subsequent screening of germplasm collections revealed genotype UC-310 with a higher degree of field resistance compared to susceptible lines RZ-209 and UC-223 (Arora *et al.*, 2004). Recent multi-location trials under arid and semi-arid conditions have emphasized the significance of early-maturing cultivars such as CZC-94, which escapes peak pathogen pressure due to its shorter growth duration (CAZRI, 2022).

Advances in molecular breeding and genomic analysis have deepened the understanding of host-pathogen interactions in cumin and related Apiaceae crops. Resistance appears to be polygenic and largely associated with defense pathways involving phenolic compounds, pathogenesis-related proteins, and antioxidant enzymes that restrict *Alternaria* colonization (Kumar *et al.*, 2018; Sharma *et al.*, 2021). Elevated activities of peroxidase (POX), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) have been reported in tolerant genotypes following infection (Meena *et al.*, 2020).

The recent integration of marker-assisted selection (MAS) and transcriptomic profiling has facilitated the identification of resistance-linked markers and defense-responsive genes. Studies by Verma *et al.* (2024) highlighted the differential expression of stress-responsive genes such as *WRKY*, *PR-1*, and *PAL* in tolerant cumin lines under *A. burnsii* challenge. Additionally, research on induced resistance using elicitors (e.g., salicylic acid, jasmonic acid, and β -aminobutyric acid) suggests that partial resistance can be enhanced through biochemical priming of defense pathways (Gautam *et al.*, 2022).

Despite these advances, achieving durable resistance remains challenging due to the high genetic variability and adaptive potential of *Alternaria* spp. Integrating host resistance with complementary strategies such as biocontrol agents (*Trichoderma* spp.) and botanicals under

an integrated disease management (IDM) framework offers a pragmatic path toward long-term control. Continuous screening of global germplasm, along with genomic-assisted breeding, is essential to develop resistant cultivars suited for future climate-resilient cumin cultivation.

D. Chemical management

A variety of studies have explored the effectiveness of different fungicides in managing *Alternaria* blight and enhancing cumin seed yield. Historically, copper-based fungicides such as Bordeaux mixture and Prenox (Chattopadhyaya, 1967) were effective against *Alternaria burnsii*. Research by Gemawat and Prasad (1969) demonstrated that applying Cuman (0.1%) and Dithane Z-78 (0.2%) twice at one-month intervals post-flowering resulted in control rates of 72.6% and 61.7%, respectively, while also boosting cumin crop yields. Patel and Desai (1971) found that treating seeds with the mercurial fungicide Ceresan (2.5 g/kg seed) and subsequent spraying with Dithane Z-78 improved control measures. Other fungicides such as Captan, Cuman, Dithane-M-45, Blitox, Plantvax, and Vitavax were also reported as effective against cumin blight. The application of Difolatan (0.15%) three times yielded optimal results in controlling the disease (Solanki *et al.*, 1973). Combining seed treatment with Bavistin (carbendazim) proved highly effective against *A. burnsii* (Lakhtaria & Pillai, 1978). Additional studies highlighted the efficacy of four applications of Dithane M-45 (0.2%) (Mehta & Solanki, 1990) and Mancozeb (0.2%) for managing the blight (Akbari *et al.*, 1996). Other promising fungicides include Propiconazole, Carbendazim combined with Hexaconazole, Iprodione, and Chlorothalonil (Sharma *et al.*, 2013).

Prophylactic sprays of 0.2% Mancozeb, Difolatan, or Zineb have been recommended at the first signs of disease or during periods of cloudy weather (Khare *et al.*, 2014a). Seven applications of Rovral 50 WP (0.2%) or Companion (0.2%) from the flowering

stage were shown to significantly reduce *Alternaria* blight and increase cumin seed yield (Khalequzzaman, 2016). Recent studies reported that Kresoxim methyl (44.3SC), Difenoconazole (25 EC), and Propiconazole (25 EC) effectively minimized disease intensity (Patel *et al.*, 2017). For optimal disease control, combinations such as Azoxystrobin with Tebuconazole at 1 L and Carbendazim with Mancozeb at 1 kg per hectare were particularly effective (Jat *et al.*, 2019b). Mixed fungicide treatments have shown success in managing *Alternaria* infections. Newer fungicides like Tebuconazole (50% + Trifloxystrobin 20% WG), Tebuconazole 2DS, and Pyraclostrobin (13.30% + Epoxiconazole 5% SE) have also shown promising results under laboratory and field conditions (Varma & Kumhar, 2023).

Recent advances (2020–2025) have considerably expanded the understanding of fungicidal control strategies against *Alternaria burnsii*, emphasizing the effectiveness of newer systemic fungicides, premix formulations, and resistance management strategies. Multiple studies from 2020 onward have reaffirmed the superiority of triazole- and strobilurin-based fungicides in controlling *Alternaria* blight under diverse agro-climatic conditions. Yadav *et al.* (2022) reported that Tebuconazole 25.9 EC at 1 mL/L significantly reduced disease severity (to ~6%) compared to Carbendazim+Mancozeb (39%) and increased cumin yield, confirming its efficiency under arid conditions. Similarly, Sharma *et al.* (2024) demonstrated that Tebuconazole 25% WG (500–750 g/ha) and Pyraclostrobin+Epoxiconazole mixtures provided the lowest disease intensities with substantial yield gains, promoting a shift toward systemic fungicide premixes for sustainable management. Makwana *et al.* (2024) also recorded the highest seed yield (907 kg/ha) and minimum blight intensity using Azoxystrobin+Tebuconazole (11% + 18.3% SC) under field trials in Rajasthan, underscoring the strong potential of QoI+DMI fungicide combinations for farmer-level applications.

In vitro investigations during 2022–2024 have

shown that difenoconazole, propiconazole, and their combinations with strobilurins achieved nearly complete mycelial inhibition at low concentrations, establishing their superiority in pre-field screening tests. Several research groups have emphasized that premix fungicides like azoxystrobin+tebuconazole and trifloxystrobin+tebuconazole not only improve efficacy but also reduce the risk of resistance development in *Alternaria* populations. Furthermore, resistance management has emerged as a central concern in cumin pathology. Continuous use of single-site fungicides (QoI, DMI, and benzimidazoles) can accelerate resistance; therefore, the adoption of alternating and mixture-based fungicidal regimes is now widely advocated.

Residue management and export compliance have also become critical issues for cumin growers. Recent reviews (2023–2024) have highlighted that overuse of Mancozeb and other high-residue fungicides can lead to rejection of exported consignments due to maximum residue limit (MRL) violations. Hence, modern formulations such as Azoxystrobin, Tebuconazole, and Trifloxystrobin with shorter pre-harvest intervals are recommended for safe use without compromising export standards. Several on-farm demonstrations have validated that replacing conventional protectants with modern premixes can reduce spray frequency, improve disease control, and ensure residue safety. Economically, triazole- and strobilurin-based fungicides have been shown to provide higher benefit-cost ratios than traditional contact fungicides. Although the initial cost of these systemic fungicides is higher, their increased persistence, lower required frequency of application, and higher yield gains make them economically advantageous for commercial cumin production systems (Yadav *et al.*, 2022).

Emerging technological trends have further refined chemical management strategies. Several researchers (2023–2025) reported the potential of nano-formulated fungicides that allow reduced dosages with enhanced

persistence and target specificity, though field-scale validation is still limited. Integration of biopesticides or plant extracts with reduced fungicide doses has also been proposed to maintain efficacy while minimizing chemical load and resistance pressure. Moreover, recent modeling approaches integrating disease forecasting and microclimate monitoring have demonstrated promise in predicting blight outbreaks, enabling targeted fungicide application and reducing unnecessary sprays.

Integrated disease management

Integrated Disease Management (IDM) represents the most holistic and sustainable strategy for combating *Alternaria blight* in cumin (*Cuminum cyminum* L.). This multifaceted approach harmonizes chemical, biological, cultural, and botanical interventions to ensure long-term suppression of *Alternaria burnsii* while minimizing environmental and health hazards. Traditional reliance on fungicides has proven insufficient due to pathogen variability, residue concerns, and resistance buildup; hence, integration with bioagents and botanicals has emerged as the modern paradigm (Shekhawat *et al.*, 2013).

Several studies have validated the synergistic efficacy of combined chemical–biological approaches. The foliar application of Tebuconazole with Azadirachtin demonstrated substantial reductions in blight severity while improving physiological and biochemical traits of cumin plants (Shekhawat *et al.*, 2013). Similarly, El-Deeb *et al.* (2016) reported that Bio-Zeid (*Trichoderma album*) combined with compost reduced disease incidence and enhanced soil fertility, thereby supporting sustainable yield improvement. Seed treatment with *T. harzianum* (8 g/kg) followed by three foliar sprays of Azadirachtin (2 ml/L) at 45–100 days after sowing was found to be particularly effective under field conditions (Chhatal *et al.*, 2017).

Recent research has shifted focus toward innovative bio-stimulants and nano-formulations. Nano-silicon (NSi) and nano-

chitosan carriers for *T. harzianum* have been shown to increase enzymatic defense activity, reduce oxidative stress, and improve volatile oil yield in cumin (Kumawat *et al.*, 2025). Similarly, essential oils (neem, clove, eucalyptus, lemon grass) and plant extracts were reported to suppress *A. burnsii* spore germination and enhance morphological traits such as plant height and umbels per plant (Rao *et al.*, 2021b; Meena *et al.*, 2023). These natural compounds not only serve as direct antifungal agents but also function as elicitors of induced systemic resistance (ISR).

Microbial consortia and bio-intensive systems have further strengthened the IDM concept. Maciag *et al.* (2023) demonstrated that a four-microbe consortium (*Trichoderma afroharzianum*, *Aneurinibacillus aneurinilyticus*, *Pseudomonas lalkuanensis*, *Bacillus licheniformis*) improved disease suppression by 32.5% and doubled yield compared to untreated checks, primarily through enhanced antioxidant enzyme activity. Likewise, integrating *T. asperellum* with composted FYM and low-dose Pyraclostrobin + Epoxiconazole sprays effectively reduced disease intensity under field conditions. Patel *et al.* (2021) also observed that Carbendazim + Mancozeb seed treatment combined with *T. viride* and neem extracts achieved 70% disease reduction, highlighting the value of complementary biological-chemical interactions.

Several new generation fungicidal combinations (Tebuconazole + Trifloxystrobin, Azoxystrobin + Difenconazole, and Kresoxim-methyl + Propiconazole) have been successfully integrated with biocontrol agents to limit resistance development while sustaining disease management efficiency. Moreover, Singh *et al.* (2024b) demonstrated that seed biopriming with *T. viride* combined with salicylic acid sprays (0.5 mM) significantly enhanced peroxidase (POX), polyphenol oxidase (PPO), and catalase (CAT) activities, reducing *Alternaria* blight severity by 60–65%.

Parallel emphasis has been placed on host resistance and eco-cultural management.

Evaluations by Jadon *et al.* (2020) indicated moderate resistance in select germplasms, suggesting the potential for breeding resistant varieties as a vital IDM component. Soil enrichment with organic matter, vermicompost, and neem cake has also been correlated with improved microbial diversity and reduced *Alternaria* inoculum load (Kumar *et al.*, 2022). Integrating resistant genotypes, organic amendments, biopriming and low-dose fungicides under rotational or need-based application could offer the most resilient management approach against evolving *Alternaria* populations in cumin ecosystems.

Conclusion

Cumin (*Cuminum cyminum* L.) plays a vital role in India's agro-economic and global spice trade, yet its productivity is severely constrained by *Alternaria* blight caused primarily by *Alternaria burnsii*. Despite extensive studies spanning nearly a century, the disease continues to pose a major challenge due to the pathogen's high genetic variability, ecological adaptability, and evolving fungicide resistance. Recent advances in molecular taxonomy, genomics and plant-microbe interactions have provided critical insights into pathogen diversity, virulence determinants, and host defense responses. However, translating these findings into field-level management strategies remains limited.

An integrated approach combining host resistance, cultural and nutritional optimization, biological control (notably *Trichoderma* spp. and beneficial rhizobacteria), and eco-safe botanicals offers a promising and sustainable solution. The recent development of potent QoI+DMI fungicide combinations also provides short-term disease suppression, but overreliance must be avoided to prevent resistance build up. Long-term resilience will depend on continuous germplasm screening, molecular breeding for durable resistance, and the deployment of predictive disease-forecasting models under changing climatic regimes.

Future research should prioritize multi-

omics-driven elucidation of host–pathogen–environment interactions, identification of resistance-linked QTLs, and formulation of region-specific Integrated Disease Management (IDM) modules. Strengthening farmer awareness and residue-free production practices is equally essential to sustain export quality and environmental safety.

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