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Navigating Alternaria Blight in Cumin over the Decades: A Critical Review for Arid and Semi-arid Regions of India

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Abstract: *Alternaria* blight management in cumin cultivation is critical due to its significant impact on both yield and quality, particularly in major exporting countries like India. This review underscores the formidable challenges posed by *Alternaria* species, particularly *A. burnsii*, which can inflict crop losses of up to 80% in severe outbreaks. A thorough understanding of the disease's etiology, symptoms, and predisposing factors is essential for effective management. To mitigate the spread of this disease, implementing cultural practices such as the use of healthy seeds, rigorous crop rotation, and timely harvesting is paramount. The application of botanical remedies and biocontrol agents has demonstrated promise in reducing disease severity while promoting sustainable agricultural practices. Although no cumin genotype has shown complete resistance to *Alternaria* blight, certain varieties have exhibited varying levels of tolerance, highlighting opportunities for breeding programs aimed at enhancing resistance. Chemical management strategies remain integral to controlling blight, with a range of fungicides proving effective against *A. burnsii*. However, the increasing concerns regarding chemical residues and the potential for pathogen resistance emphasize the necessity of integrated disease management approaches. By combining cultural methods, biological control, and judicious chemical treatments, farmers can adopt a comprehensive strategy to combat this resilient pathogen. Future research should prioritize the development of innovative and sustainable solutions for managing *Alternaria* blight, enabling cumin farmers to maintain productivity and quality. By disseminating advancements in disease management practices to farming communities, we can enhance the profitability and sustainability of cumin cultivation, thereby securing the livelihoods of those who depend on this invaluable spice.

Key words: *Alternaria*, etiology, epidemiology, predisposing factors, bio-agents

India is one of the world's leading producers, exporters, and consumers of seed spices. Cumin (*Cuminum cyminum* L.), a dried seed from the Umbelliferae family, is one of the key spices. Believed to be native to the Mediterranean region (Kunal *et al.*, 2017), cumin is extensively cultivated in countries like Tajikistan, Turkey, Uzbekistan, Morocco, India, Egypt, Mexico, Syria, Pakistan, and Chile (Azeez *et al.*, 2008). It goes by various names across the globe, including "Jeera" in Hindi, "Kumin" in German, "Komijn" in Belgium and "Faux Anis" in French (Didwania, 2019). It is an essential spice extensively used in Indian cuisine for its distinctive flavor and aroma. It contains several phytochemicals with beneficial properties, including anti-flatulent, carminative, and antioxidant effects, largely attributed to its aldehydes, volatile oil, and cuminol content (Deepak *et al.*, 2008; Patel *et al.*, 2017). Additionally, cumin seeds are rich in minerals, essential antioxidant vitamins, flavonoids, carbohydrates, proteins and fats.

It is grown in an area of 9,02,010 ha, and the production in 2022-2023 was 62,7031 tons (Fig. 1). India is the largest exporter of cumin seeds accounting for about 75% of the global export market. Since 2011, India's share in the global cumin seed market has grown by 30.4%. There is high demand for Indian cumin seeds in countries like China, Bangladesh, and the USA. They are the major importers of Indian cumin seeds, collectively accounting for 41.9% of India's cumin exports. The export value to China has surged from US$ 0.26 million in 2015 to US$ 106.17 million in 2019. Likewise, exports to Bangladesh and the US have grown at compound annual growth rates (CAGRs) of 65.5% and 7.8%, respectively, indicating a rising global demand for Indian cumin seeds (Bhardwaj, 2021). It is cultivated mainly in the Indian states of Rajasthan and Gujarat, which offer favorable semi-arid climates and soil conditions. This spice is vital for the livelihoods of farming communities across its cultivation areas. However, diseases like wilt, *Alternaria* blight, and powdery mildew, coupled with nutrient deficiencies, cause significant productivity losses (Dange *et al.*, 1992; Sharma *et al.*, 2013) (Fig.1). Among these challenges, *Alternaria* blight has emerged as a particularly devastating threat, causing significant yield losses up to 85% (Varma *et al.*, 2022). Additionally, issues such as high chemical residues in cumin seeds, the rise of pathogen resistance, and the continuous cultivation of disease-susceptible varieties have exacerbated difficulties for farmers. These factors sometimes lead to complete rejection of the exported consignment.

This review examines the exient of damage, symptoms, etiology and successful management approaches of *Alternaria* blight established over the past three decades in various cumin-producing nations. The aim is to encourage researchers to enhance their endeavors in developing more efficient blight management strategies and to share these advancements

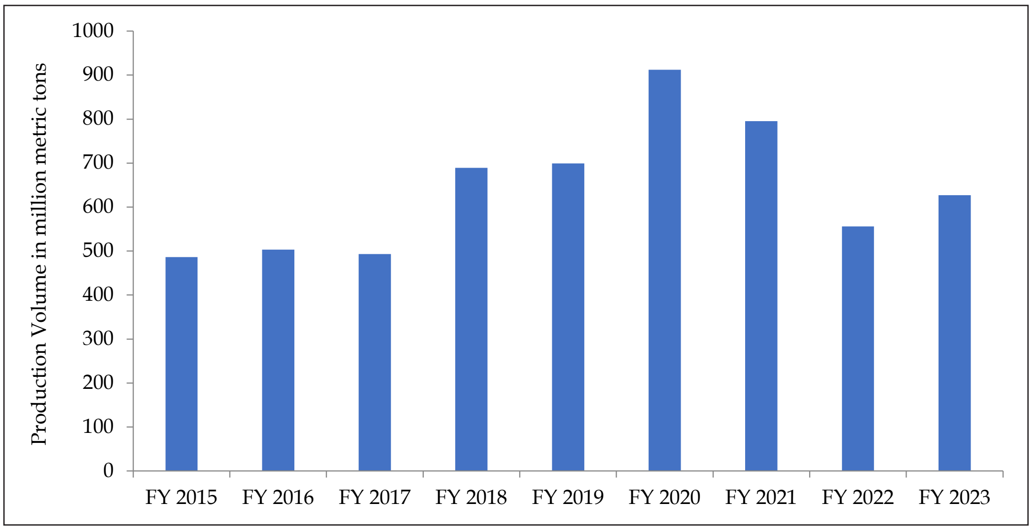

Fig. 1. Production volume of cumin across India from financial year 2015 to 2022, with an estimate for 2023 (Source: Statistica 2025; Spice board 2023).

Fig. 2. Alternaria blight infected host plants of cumin.

with cumin farmers, thus ensuring profitable cumin cultivation.

Extent of damage: The first report of cumin blight due to *Alternaria burnsii* in India came from Gujarat by Uppal *et al.* (1938) and subsequently reported in Rajasthan by Joshi (1955) and Patel (1968). This pathogen was later identified by Shakir *et al.* in 1995. *A. burnsii* has since been found to be widespread in arid and semi-arid regions worldwide, with severe incidences reported in countries such as India, Iran, Tajikistan, Uzbekistan, Egypt, Syria, Turkey, Morocco, Chile, Mexico, Bulgaria, and Cyprus.

This disease can cause crop losses of up to 80%, manifesting annually in the most productive cumin-growing areas. In India, states particularly affected by yield losses include Rajasthan, Gujarat, Haryana, and West Bengal, where losses can reach up to 70% (Shekhawat *et al.*, 2013). For instance, Sharma *et al.*, 2013 noted 80% blight incidence in cumin. Bandopad**hyay** *et al.* (1980) reported severe blight at the flowering stage, affecting nearly 85% of the plants. Bhatnagar *et al.* (1998) found that the severity of the disease varied between 16% and 65%. In Haryana, total crop failure occurred during heavy rainfall at the flowering stage (Mehra *et al.*, 1998; Kumar *et al.*, 2002). A survey in the Jodhpur, Nagaur and Jaisalmer districts of Rajasthan revealed disease severity ranging from 5% to 60%, with the highest intensity observed during flowering and umbel formation. Furthermore, Mawar reported that seeds harvested from infected plants were often deformed and unpalatable (Unpublished).

Symptoms: The disease impacts all aerial parts of cumin plants, exhibiting various symptoms such as tip burning and brown to black spots on leaves, stems, and inflorescences, ultimately leading to the blighting of many plant sections (Fig. 2) (Patel and Desai, 1971; Chand *et al.*, 2000; Wadud *et al.*, 2017). Initially, affected plants display small necrotic spots on all aerial parts, particularly on the tips of young leaves. These spots enlarge and merge, potentially resulting in the death of the entire plant or its affected parts (Sharma, 2010). Affected plants may also show purplish, brownish, or blackish lesions. The severity of the disease peaks under humid conditions (Khare *et al.*, 2014; Khalequzzaman, 2016). Infections occurring during the flowering stage can destroy the umbels, leading to failed seed development in diseased plants. If seeds do develop, they often appear light and blackish, causing significant losses for growers. During winnowing, shriveled seeds are easily blown away (Didwania, 2019).

Etiology of the pathogen: *Alternaria* was first identified by Nees von Esenbeck (1816) and Berkeley (1836). It has been documented that cumin blight is caused by several species, including *Alternaria alternata*, *A. burnsii*, *A. tenuissima*, *A. gaisen*, *A. interrupta*, and *A. dumosa* (Wadud *et al.*, 2021). The genus *Alternaria* is classified within the kingdom Fungi, phylum Ascomycota, class Deuteromycetes (asexual Ascomycetes), subclass Hyphomycetidae, order Moniliales, and family Dematiaceae (Alexopoulos *et al.*, 1996).

Alternaria species produce asexual spores (conidia) measuring between 160 and 200 µm in length, which are formed by conidiophores exhibiting various horizontal and longitudinal septations. These characteristics are useful for distinguishing between species. The conidial characteristics of *Alternaria burnsii* and its closely related species are given in Table 1. As necrotrophic pathogens, they eliminate host cells prior to colonization by secreting toxins such as alternariols, altertoxins, and tenuasonic acid, which induce cell death either

Table 1. Conidial characteristics of Alternaria burnsii and its closely related specie

Species	Conidia				References
	Size (µm)	Shape	Septa		
			Transverse	Longitudinal	
A. burnsii	16~60 (90) × 6.5~14 (~16)	Long ellipsoid, obclavate or ovoid	2~6 (11))	0~2 (~4)	Paul *et al.*, 2015
A. tomaticola	30~40 × 9~12	Ellipsoid or ovoid	6~7	1 (~2)	Simmons, 2007
A. longipes	12~35(~48)× 5~12 (~14)	Narrow-ovoid or ellipsoid	Uncommon 3~7	No or 1 (~3)	Simmons, 2007
A. tomato	30~50 × 10~13	Narrow-ovoid	6~9	1 (~2)	Simmons, 2007

Source: Paul et al., 2015.

by activating programmed apoptotic pathways or by causing direct damage leading to necrosis (Thomma, 2003).

There is considerable variability among *Alternaria* species in terms of their cultural, morphological, pathogenic, and molecular traits (Pipliya and Jadeja, 2008). A survey conducted in the Jodhpur, Nagaur, and Jaisalmer districts by team of scientist revealed differences among cultural isolates, with colonies displaying variations in color, growth patterns, and morphology (Fig. 3A). Observations under a light microscope indicated differences in spore shape, septation, presence or absence of a beak, as well as length and dimensions (Fig. 3B) (Ritu Mawar, unpublished data). Similar studies have been done by Nasreen *et al* 2017 on vegetative and reproductive growth of Alternaria. Sekhawat *et al.* (2013) have reported five pathogenic groups of which the isolate from Jalore district was most virulent.

Predisposing factors for disease development

Alternaria species can survive in the form of spores and mycelium within infected plant residues or on seeds (Kakraliya *et al.*, 2022). Seed-borne fungi may attack seedlings, leading to necrotic lesions (Khare *et al.*, 2014). The fungus typically thrives and produces spores on plant residues during rainy conditions, heavy dew, or when soil moisture levels are high. Spores can be wind-blown or splashed onto plant surfaces, allowing them to penetrate the host either through wounds or stomata. The disease affects all aerial parts of cumin plants, including stems, leaves, fruits, pods, and umbels (Khalid *et al.*, 2004; Deshwal, 2004).

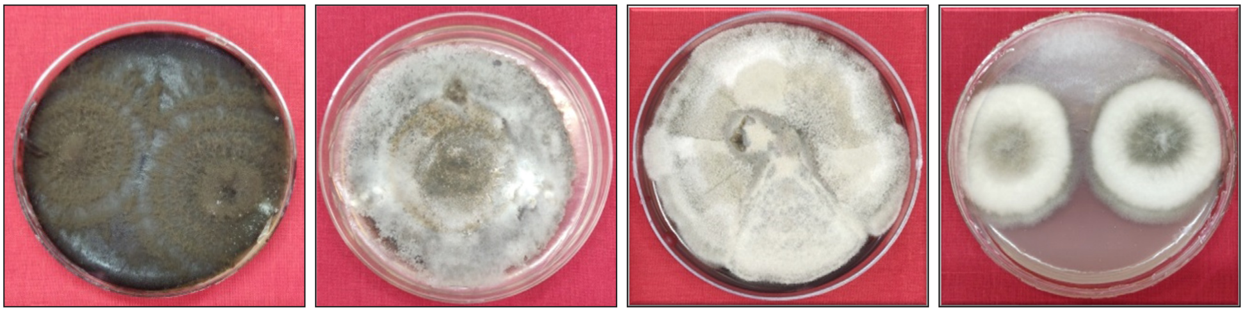

Fig. 3A. Pictures showing differences in isolates of Alternaria bursii for colour, growth pattern and morphology

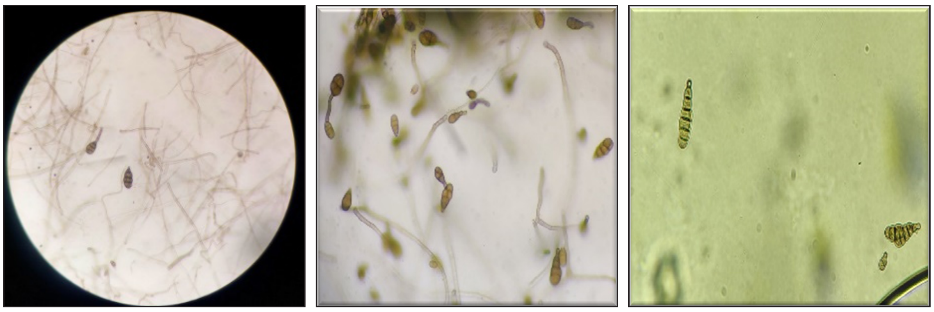

Fig. 3B. Light microscope images showing differences in isolates of Alternaria bursii for spore shape, septation and beak presence

According to Lakra (2005) the incidence of *Alternaria* blight increased with the increase in the duration of dewfall, leaf wetness, relative humidity, congenial temperature and number of rainy days. Arora *et al.* (2008) planted 25 cumin cultivars at 5 days interval from 15th October to 15th December and observed that period of ten weeks from sowing was favorable for initiation and spread of the blight. December sown crop had least disease incidence while highest blight incidence was in October sown crop (Champawat and Singh, 2008). High humidity during flowering and fruit setting are the most vulnerable stages of crop favors the development of *Alternaria* blight in cumin (Gemawat and Prasad, 1972; Khare *et al.*, 2014). If relative humidity exceeds 91.5%, a large number of mature spores can be produced within 24 hours (Humpherson-Jones and Phelps, 1989). Additionally, conidia can survive in warm and dry conditions for several months. Cloudy weather combined with warm and moist conditions increases disease incidence and can lead to rapid spread throughout the field, preventing seeds from maturing fully and potentially resulting in complete crop failure (Pipliya and Jadeja, 2008). Temperature 23-28°C has been found optimum for development of blight in cumin crop (Gemawat and Prasad, 1972). Early planting results in greater severity of the disease and the pathogen is seed borne and seed transmitted and also soil borne surviving in crop debris (Khare *et al.*, 2014).

Identification and characterization of Alternaria spp.

Identifying and characterizing the blight pathogen involves cultural, morphological, and molecular techniques, which enhance understanding and classification, ultimately aiding in the development of effective management strategies for blight at the field level.

Cultural: The mycelial growth of *Alternaria* varies across different media with diverse chemical compositions. Bhatnagar and Kant (1995) noted that *A. burnsii* exhibited maximum growth and sporulation on Richard's medium. In a study, isolate AB-01 of *A. burnsii* demonstrated optimal growth on potato dextrose agar (PDA) after four and seven days of incubation (Singh *et al.*, 2016). Czapek's Dox Agar also supports robust growth and spore formation of *A. burnsii* isolates. The initial fungal growth appears light green, occasionally whitish green, and eventually turns grey to black, characterized by a colony margin that ranges from dirty white to brownish, with a fluffy radial, irregular, and knotting growth pattern (Sawant and Parmar, 2019).

Morphological: The various *Alternaria* species affecting cumin show considerable diversity in their growth patterns, and their spore morphology varies widely under microscopic examination. The largest conidial sizes recorded were 88-111×26-32 µm (with beak) and 30-38×14-18 µm (without beak) for isolates UDP Ab-1, while the smallest sizes of 70-88×25-32 µm (with beak) and 31-39×15-19 µm (without beak) were found in isolate JLR Ab-1 of *A. burnsii*. In contrast, *A. alternata* isolates exhibited the largest conidial sizes of 38-48×9-11 µm (with beak) and 30-38×11-14 µm (without beak) in isolate JSL Aa-2 (Singh *et al.*, 2016). Conidiophores from *A. burnsii* isolates varied, being branched, erect, straight, irregularly bent, or geniculate, while conidia displayed a wide range in size, number of septa, beak length, and sporulation frequency (Singh *et al.*, 2016). The conidia are oval to oblong with 3 to 6 transverse septa, forming chains of 3 to 8 spores with rounded bases. The conidiophores are branched and septate, consisting of 3 to 5 cells (Varma *et al.*, 2022). Some more such studies

Molecular: Molecular tools are increasingly employed to delineate fungal species and study their diversity (Benali *et al.*, 2011). Phylogenetic grouping based on the internally transcribed spacer (ITS) gene sequence using MEGA5.6 and factorial analysis via DARwin5 revealed two distinct groups for *A. burnsii* (Singh *et al.*, 2018). Ozer and Bayraktar (2019) developed primer pairs that allow for rapid and accurate detection of *A. burnsii* in cumin seeds. These primers demonstrated high sensitivity in both conventional and real-time PCR assays, enabling detection and quantification of the pathogen even at low infestation levels. Additionally, Sawant and Parmar (2019) analyzed the molecular variability of A. burnsii across fifteen isolates from key cumin-producing regions in Gujarat. They selected ten RAPD primers for their repeatability, resulting in 622 bands and 84 loci, with an average polymorphism of 91.51%.

Management strategies

The rapid spread of the disease necessitates the implementation of prophylactic measures for effective prevention against blight (Didwania, 2019). One of the primary management steps for any foliar disease is the disinfestation of tools used for spraying (Panth *et al*., 2020). Various management strategies have been developed to reduce blight incidence in the field, enhancing the profitability of cumin cultivation.

Cultural management: To effectively manage cumin blight, several cultural practices have been studied. Infected seeds and residual plant debris in fields can act as significant sources of inoculum (Uppal *et al*., 1938; Patel and Desai, 1971; Gemawat and Prasad, 1972) Additionally, promptly plowing under crop debris can reduce inoculum growth and survival (Meena *et al*. 2021).

Early harvesting is another strategy that can prevent yield losses due to blight (Gemawat and Prasad, 1972). It is also important to remove any old crop residues from infected fields. Practicing crop rotation, at least every two years, is essential for breaking down agricultural leftovers and reducing the risk of disease recurrence. Other beneficial practices include wider row spacing, breaking up compacted soil layers, and planting on raised ridges, all of which can help decrease leaf wetness and soil moisture conducive to the disease. Generally, cumin grown in stressed and inadequately nourished soil is more susceptible to *Alternaria* leaf blight. Apart from this, balanced crop nutrition especially of potassium should be provided. The best way to proactively reduce the severity of the blight diseases is to use vigorous, healthy and treated seeds for reducing or eliminating potential inoculum source (Meena *et al.* 2021)

Management through botanicals and bio-control agents: "Green pesticides" encompass a variety of naturally derived pest management strategies, including plant extracts, secondary metabolites, and plant-based pesticides (Koul ***et al***., 2008). Often referred to as botanical pesticides, these substances can serve as repellents, fungicides, and bactericides, existing either as isolated compounds or complex mixtures (Campos *et al*., 2019). Although sourcing biopesticide plants can be challenging due to their limited commercial cultivation, research on botanical pesticides has surged in the past two decades (Isman, 2020).

One notable example is azadirachtin, an active compound found in neem formulations, which has shown considerable effectiveness against *A. burnsii* under *in vitro* conditions (Shekhawat *et al*., 2013). Extracts from *Aloe vera*, *Calotropis procera*, and *Eucalyptus globulus* at a concentration of 10% have also demonstrated inhibitory effects on both the growth and spore germination of *A. burnsii* in both *in vitro* and *in vivo* studies (Gangopadhyay *et al*., 2010). Garlic extract (*Allium sativum*) has proven to be particularly effective *in vitro* and has reduced disease severity while enhancing yield in field conditions (Kakraliya *et al*., 2022). Additionally, extracts from turmeric and ginger rhizomes have been shown to effectively inhibit the growth and spore germination of Alternaria blight (Pipliwal, 2013).

Biological control fundamentally aims to decrease disease incidence through the direct or indirect use of microorganisms (Shurtleff and Averre, 1997). *Trichoderma harzianum* has exhibited significant inhibition of *A. burnsii* mycelial growth *in vitro*. When applied in the field as a soil treatment, seed treatment, or foliar spray, *T. harzianum* has resulted in notably lower blight incidence, highlighting its potential for sustainable management of *Alternaria* blight in cumin (Deepak *et al*., 2008). Other beneficial species, such as *T. viride*, *T. hamatum*, and *A. awamori*, have also inhibited the growth of *A. alternata in vitro* (Ghosh *et al*., 2002; Monaco *et al*., 2004). Moreover, seed treatment with Mycostop, a formulation of *Streptomyces griseoviridis* spores and mycelium, has proven effective in managing Alternaria disease (White *et al*., 1990).

Host plant resistance: While no cumin genotype in India exhibits a high level of resistance to *Alternaria* blight, several studies have identified varieties with varying degrees of tolerance. For instance, Edison and Kallupurackal (1989) reported that the RZ-19 and UC-198 varieties displayed some tolerance to blight in Rajasthan. Subsequent research by Edison *et al.* (1991) noted that varieties such as MC-43, Gujarat cumin-I, RZ-19, and Gujarat cumin-2 also showed resistance to the disease. Mehra *et al.* (2002) identified five genotypes viz., RZ-209, RZ-19, UC-216, UC-198, and

HZ-21 as moderately resistant to Alternaria blight. Among twelve varieties screened in a pot house, UC-310 exhibited high resistance, while RZ-209 and UC-223 were classified as highly susceptible, and RZ-19 was noted as moderately susceptible to highly susceptible (Arora *et al.*, 2004).

Additionally, AC-167, UC-198, UC-216, RZ-209, and JC-11 have been recognized for their moderate resistance under field conditions (Sunder, 2005). Notably, the CZC-94 cultivar has demonstrated a rapid growth cycle, maturing in just 106 days during multi-location trials in the arid regions of Rajasthan. This early maturation may help minimize disease severity by allowing the plants to avoid pathogen exposure during critical developmental stages (CAZRI, 2022).

Chemical management: Various studies have explored the effectiveness of different fungicides in managing Alternaria blight and enhancing cumin seed yield (Fig 4). Historically, copper-based fungicides such as Bordeaux mixture (Joshi, 1955) 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^{-1} seed) and subsequent spraying with Dithane Z-78 improved control measures. Other fungicides such as Captan, Cuman, Dithane-M-45, Blitox, Plantvax, and Vitavax have also been reported as effective against cumin blight (Solanki *et al.*, 1973). The application of difolatan (0.15%) three times yielded optimal results in controlling the disease (Solanki *et al.*, 1973). Lakhtaria and Pillai, 1978 used carbendazim as a seed treatment and spray which proved highly effective against *A. burnsii* (). Additional studies highlighted the efficacy of four applications of Dithane M-45 (0.2%) (Mehta and 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.*, 2014). 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 liter and carbendazim with mancozeb at 1 kg ha^{-1} were particularly effective (Jat *et al.*, 2019). Mixed fungicide treatments have been shown to successfully manage *Alternaria* infections. Newer fungicides like Tebuconazole (50% + Trifloxystrobin 20% WG), Tebuconazole 2DS, and Pyraclostrobin (13.30% + Epoxiconazole 5% SE) have also shown promising results in laboratory conditions (Varma and Kumhar, 2023) (Fig. 4).

Integrated disease management

To address the significant economic losses caused by Alternaria blight, an integrated approach is essential for effective control of this resilient pathogen. A promising strategy involves combining fungicides and botanicals; for instance, the mixture of tebuconazole and Azadirachtin has proven significantly effective when used as a foliar spray (Shekhawat *et al.*, 2013). Research by El-Deeb *et al.* (2016) demonstrated that the foliar application of the biocide Bio-Zeid (*Trichoderma album*) and compost substantially reduced the severity of cumin blight. A comprehensive treatment strategy, which included seed treatment with *Trichoderma harzianum* at 8 g/kg, followed by three foliar applications of Azadirachtin (2 ml/liter) at intervals of 45-60, 60-75, and 90-100 days after sowing, was found to be highly effective in managing the disease (Chhatal *et al.*, 2017).Additionally, an emulsion of dried spores of *T. harzianum* at a concentration of 1×10^6 spores/ml was particularly successful in suppressing Alternaria blight, with nano silicon (NSi) also showing beneficial effects on yield and volatile oil content in the seeds (Aziz *et al.*, 2021). Furthermore, the application of botanicals and ess oils resulted in significant

Bordeaux mixture (1955- 1967)

↓

Cuman and Dithane Z-78 (1969)

↓

Difolatan (0.15%) (1973)

↓

Carbendazim (1978)

↓

Dithane M-45 (1990)

↓

Mancozeb (1996)

↓

Propiconazole, carbendazim + hexaconazole iprodione & chlorothalonil (2013)

↓

Mancozeb, Difolatan or Zineb (2014)

↓

Rovral (50 WP) or Companion (2016)

↓

Kresoxim methyl difenoconazole and propiconazole (2017)

↓

Azoxystrobin with tebuconazole and carbendazim with mancozeb (2019)

↓

Tebuconazole + Trifloxystrobin 20% WG)
Tebuconazole 2DS, Pyraclostrobin + Epoxiconazole (2023)

Fig. 4. History of chemical fungicides used in management of cumin blight.

improvements in plant height, branch count, number of umbels per plant, and overall yield, while simultaneously reducing disease intensity (Rao *et al.*, 2021).

Conclusions

Managing *Alternaria* blight in cumin cultivation is crucial due to its significant impact on yield and quality, especially in major exporting countries like India. This review highlights the challenges posed by *A. burnsii*, which can cause crop losses of up to 80%. Understanding the disease's etiology, symptoms, and predisposing factors is essential for effective management. Cultural practices, including the use of healthy seeds, crop rotation, and timely harvesting, are vital for mitigating disease spread. While no cumin genotype shows complete resistance, some varieties demonstrate varying tolerance levels, suggesting breeding opportunities. Chemical management with effective fungicides remains important, but concerns about chemical residues and pathogen resistance underline the need for integrated approaches. Combining cultural methods and biological controls with chemical treatments can create a comprehensive strategy. Future research should focus on innovative solutions for sustainable management of *Alternaria* blight. Sharing advancements in disease management can enhance the profitability and sustainability of cumin farming.

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Author Contributions

Conceptualization, supervision, Ritu Mawar; methodology, writing original draft, Nitika Kumari V.K. Kardam and Divya Gurjar; review and editing, revision, Ritu Mawar and Saranya R. All authors have read and agreed to the published version of the manuscript.

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