REVIEW ARTICLE

A Critical Review on Management Approaches for Brown Spot (*Bipolaris oryzae*) Disease in Rice (*Oryza sativa L.*)

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Abstract

Rice is a vital food crop in India and globally, with a significant portion grown during the Kharif season. However, rainfed cultivation remains substantial (41%) due to limited irrigation (59%). Brown leaf spot, caused by *Bipolaris spp*., is a major threat, causing significant yield and quality losses (averaging 5% in lowland rice in Southeast and South Asia, up to 45% in severe cases; the 1943 epidemic contributed to the Great Bengal Famine). Addressing this threat under changing climatic conditions requires improved management. Farmers use various strategies, but resistant varieties offer the most economical and effective long-term solution. Judicious use of fungicides and phytoextracts is necessary, given environmental changes. Strengthening natural defences through the use of plant activators and addressing nutrient deficiencies are essential strategies. Adopting an integrated approach that incorporates resistant varieties, proper nutrient management, natural by-products, induced resistance mechanisms, cultural methods, biological control agents, and minimal chemical inputs offers the most effective means of managing rising disease pressures and securing future food supplies amid a changing climate.

Keywords: Brown spot disease, Rice, Cultural management, Biological management, Chemical management.

Highlights:

Brown spot disease, caused by *Bipolaris oryzae*, severely affects rice yields, especially in rainfed regions.

Yield losses range from 5 to 45%, with historical epidemics such as the 1943 Bengal famine linked to the disease.

Climate change exacerbates the disease's impact, demanding improved and adaptive management strategies.

Cultivating resistant rice varieties remains the most cost-effective and sustainable approach.

Fungicides and plant-based phytoextracts should be used judiciously to minimize environmental harm.

Enhancing natural plant defence with activators and correcting nutrient deficiencies are vital components.

Cultural practices and biocontrol agents reduce pathogen pressure and improve crop health.

An integrated disease management (IDM) approach ensures long-term sustainability and food security.

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Introduction

Oryza sativa L., widely known as rice, serves as a vital food source for economically disadvantaged populations worldwide, forming a staple diet for a significant portion of the global population. Nevertheless, rice production faces substantial reductions due to both biotic and abiotic stresses. Among the biotic factors, infections caused by fungi, bacteria, viruses, and nematodes are major reasons for declines in both yield and grain quality. It is estimated that globally, rice diseases result in annual losses of approximately $5 billion. Fungal infections, in particular, represent a major threat to rice cultivation. One of the most detrimental diseases is brown spot, caused by *Helminthosporium oryzae* (currently known as *Bipolaris oryzae*), which has historically impacted rice production across several regions. This pathogen is especially widespread in areas experiencing high rainfall, such as West Bengal, the Malabar coast, Assam, and the Himalayan foothills in India. Its occurrence has been recorded across nearly all rice-producing countries, including Japan, China, Bangladesh, Sri Lanka, Iran, as well as various nations in Africa, the Americas, and Southeast Asia. Brown spot disease tends to flourish in soils characterized by low pH and insufficient nutrient levels, particularly potassium (K_2O). Historically, it played a significant role in the Bengal famine of 1942–43, causing widespread crop failure and contributing to the deaths of around 2 million people. Beyond rice, this fungus also infects other crops like oats, rye, wheat, sugarcane, sorghum, *Brachiaria decumbens*, and *Panicum maximum*, showcasing its extensive pathogenic range. The disease impacts rice plants from the seedling phase through maturity, leading to a reduced leaf area index (LAI), early shoot senescence, a decline in tiller production, and diminished grain quality and weight, especially under nutrient-deficient conditions. It is often termed the "poor rice farmer's disease"

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due to its high incidence in less affluent farming communities. Environmental parameters, including temperature, humidity, and rainfall during the cropping period, heavily influence the disease's development and severity. Effective management of brown spot requires an integrated strategy involving resistant cultivars, chemical fungicides, biological agents, and agronomic practices. Despite these efforts, the disease remains a persistent challenge. Being seed-borne, it can spread through contaminated seeds, plant debris, alternative host plants, and infected irrigation water. While chemical control measures have been effective, they raise environmental concerns. Conversely, biological control techniques have demonstrated promising outcomes under laboratory and field conditions. To bolster disease resistance, breeding initiatives should emphasize the incorporation and pyramiding of multiple resistance genes and quantitative trait loci (QTLs), as suggested by Kumar *et al*. (2017).

History and importance of *Bipolaris spp*

In 1900, Breda de Haan initially identified the causal agent of rice brown spot as H. oryzae. Subsequently, Drechsler (1934) proposed transferring it to the genus Cochliobolus, a classification later formalized by Dastur in 1942. Subramanian and Jain (1966) further reclassified the fungus as Drechslera oryzae, and owing to its characteristic germination from both ends of the conidia, it was ultimately renamed *Bipolaris oryzae*. Presently, the accepted scientific name is Cochliobolus miyabeanus (Drechsler ex Dastur). According to Motlagh and Kaviani (2008), B. *victoriae* (*C. victoriae*) is the dominant brown spot pathogen in Iran, followed by B. *bicolor*, B. *oryzae* (*C. miyabeanus*), and B. indica. The pathogen forms intra- and intercellular mycelium within infected tissues, creating mats that range in colour from greyish brown to dark brown. Its pigmentation can vary between grey, olive, and black hues. Sporophores emerge through the stomata, usually in groups of 3–5, and are characterized by an upright posture, geniculate bends, thickened tips, and a pale olive base. Fig. 1 represents the fungal culture of B. oryzae.

Mature conidia, typically consisting of 5–10 septa, are widest at their center and may appear slightly curved. Conidial germination typically occurs through two polar germ tubes at the terminal ends, although immature conidia can germinate through intermediate cells. Additionally, conidial measurements have been observed to differ across various countries in *B. oryzae* (*H. oryzae*) conidial dimensions in different countries (Table 1). Considerable variation exists in the dimensions of conidiophores and conidia across different regions, with recorded measurements of 24 to 122 × 7 to 23 mm in China, 45 to 106 × 14 to 17 µm in India, 15 to 132 × 10 to 26 mm in Japan, 90 × 16 mm and up to 35 to 170 × 11 to 17. The shape of the conidia was observed to differ among isolates from various countries, a variation that was attributed to environmental influences (Emoto, 1925).

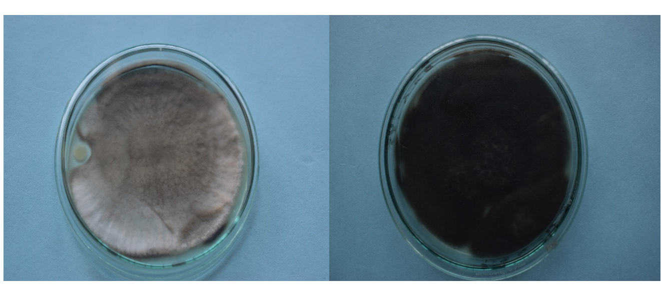

Fig 1: Fungal culture of B. *oryzae*

The optimum temperature for conidial germination is approximately 25°C, whereas maximum mycelial growth is observed near 27°C. Conidia are capable of developing across a temperature range of 5 to 38°C and within a pH spectrum from 2.6 to 10.9, with ideal conditions being a pH of 6.8 to 7.0 (Amadioha, 2002). Sporulation is influenced by light regimes; alternating light and dark periods favor conidial production, whereas blue light suppresses and near-UV light enhances it. Some artificial or natural media fail to support sporulation under varying conditions. Nevertheless, media supplemented with starch, sucrose, or mannose, like Richard's medium, promote sporulation, particularly when paired with carboxy cellulose. Peptone stands out as the most effective nitrogen source, although urea, potassium nitrate, and calcium nitrate also support fungal development. Ammonium-based nitrogen sources are more beneficial than nitrates, and the presence of amino acids further enhances fungal growth. Certain vitamins, such as biotin and thiamine, are also critical for optimal fungal development (Ou, 1985). Various studies have determined the best media for cultivating *B. oryzae*. That PDA, rice leaf agar, and maize meal agar yielded the most vigorous growth. Arshad *et al*., (2013) reported that PDA and malt extract agar supported optimal growth at 28°C after 96 hours. Additionally, detached rice leaves and rabbit food agar showed high levels of sporulation. Rice husk agar combined with near-UV light significantly increased conidia production. Suggested PDA, maize-based media, and perlite as suitable substrates for field inoculum production. Enhanced bipolar germination was also observed with longer incubation periods on PDA, water agar, and rabbit food agar (Paz *et al*., 2006). Several studies have shown that the fungus can secrete phytotoxins in culture. (Evidente *et al*., 2019) reported visible injury to rice plants following exposure to culture filtrates. Toxic compounds such as ergosterol, cochliobolin, and ophiobolin, extracted from infected plant tissues, were demonstrated to inhibit the growth of roots, shoots, and leaves. Copper oxychloride has been shown to effectively neutralize these toxins. Moreover, the fungus produces host-specific toxins that weaken the plant's defense mechanisms by decreasing phenolic compound levels and inhibiting phenylalanine ammonia-lyase (PAL) activity in rice leaves (Vidhyasekaran *et al*., 1992), ultimately resulting in the typical brown spot symptoms. These toxins also impair seed germination and reduce overall plant vigor. The sexual stage (teleomorph) of the pathogen, *C. miyabeanus*, has been documented by several researchers. Its perithecia are globose to slightly depressed, with walls that are dark yellow-brown and measure between 560–950 × 368–377 µm. Asci are cylindrical to fusiform in shape (142–235 × 21–36 µm), while ascospores are elongated, coiled, hyaline to light olive-green, with 6–15 septa, and dimensions ranging from 250–469 × 6–9 µm. Dastur (1942) first described this sexual stage in natural conditions, and Tsuda (2000) successfully induced it artificially using Sachs agar with rice straw at 24°C within 25 to 30 days. The fungus is heterothallic, meaning that sexual reproduction requires compatible mating

Table 1: B. *oryzae* (*H. oryzae)* conidial dimensions in different countries

Country	*Conidia (mm)*	*References*
Indonesia	90 × 16	Breda de Haan (1900)
U.S. A	35–170 × 11–17	Drechsler (1923)
Japan	15–132 × 10–26	Nisikado and Miyake (1922)
India	45–106 × 14–17	Sundararaman (1922)

types, but maternal traits needed for successful reproduction are often lost during continuous subculturing. Considerable genetic and morphological variability exists among *B. oryzae* isolates. Kamal and Mia (2009) analysed 152 isolates from Bangladesh and classified them into 12 DNA fingerprint groups with approximately 75% similarity; however, they found no direct correlation between genetic variation and pathogenicity. Cross-host infection studies revealed that isolates obtained from rice were capable of infecting other crops such as sugarcane, barley, oats, sorghum, and maize. Some wheat-derived isolates were also found to infect rice plants. Similarly, Serghat *et al*. (2005) demonstrated that isolates from *Echinochloa phyllopogon*, oat, wheat, and Phragmites australis exhibited high pathogenicity toward rice.

Symptomatology and pathogen identification

Typical brown spots with a grey or white core that resemble sesame seeds are one of the leaf symptoms. These spots can be circular to cylindrical in form. As individual spots coalesce, the leaves gradually turn brown and scorched, eventually leading to their death. The grains that develop from infected glumes become shriveled and discolored. This grain discoloration is attributed to *B. oryzae* (Bhat *et al*., 2009). The disease causes rice plants to become less capable of photosynthesising, which leads to the eventual scorching and death of the leaves. It also causes blighting of coleoptiles and the appearance of oval, dark brown to purplish-brown patches on the leaves and the diseased leaves' early withering (Zadoks, 2023). Some of the observed physical symptoms and microscopic characterization from the experiment are represented below in Fig.2 (a),(b) and (c).

On synthetic media, B. *oryzae* exhibits a cottony mycelial growth with colours ranging from dark grey to black or greenish. Under the microscope, its spores appear cylindrical to fusiform, light to dark brown in colour, and curved, with septate conidia. The pathogen exhibits bipolar germination morphologically, with a single terminal spore and a conidiophore present. The fungus started as a white mycelium, turned dark brown with septation, and eventually developed conidiophores that were brown in colour, multi-septate, and bearing conidia on their tips. Conidia were fusiform, curved, or slightly curved; they were hyaline at first and became brown at maturity, with a hilum at the base Fig 3 (a).

Disease cycle and mechanism of disease development

Various studies have shown that *B. oryzae,* the pathogen responsible for brown spot disease in rice, is capable of surviving in soil, straw, grains, and infected plant debris such as stubble for up to two to three years, serving as a crucial source of primary inoculum (Ou, 1985). Additionally, several weed species have been recognized as alternate hosts, acting as reservoirs for the pathogen. A sensitive baiting method has been designed for the quantitative detection of *B. oryzae* in soil (Bag *et al*., 2021). The fungus can also persist in seeds, where infected seeds initiate primary infection by forming necrotic lesions on coleoptiles and early leaf sheaths, leading to the production of airborne conidia that drive secondary infections. Although conidia are more abundant under cool and humid conditions, they can be present throughout the year. The infection process involves the penetration of host tissues by infection pegs formed from appressoria (Thuy *et al*, 2023). Rice leaf exudates, containing amino acids like glutamic acid, methionine, aspartic acid, and alanine, have been found to promote fungal colonization. Infected seeds often harbour the pathogen in both the seed coat and endosperm. Vu-Van and Sangchote (2006) reported that the rachilla exhibited the highest infection rates of *B. oryzae*, followed by the endosperm, embryo, palea, and sterile lemma in affected rice grains. Transmission rates varied between 57 to 77% using blotter and tube agar methods, with visible symptoms

Fig 2: (a). Symptoms (a) and (b) are typical brown spot-on rice leaf, (c) Discoloured brownish grains of infected glumes.

Fig 3: (a)Microscopic pictures of bipolar germination of spores and fusiform conidia with hilum at the base arise from a single multi-septate conidiophore.

on coleoptiles and roots appearing within 7 to 14 days, and on the first leaves within 3 to 4 weeks. Severe infections frequently led to seedling death through wilting and widespread tissue damage. Environmental factors, particularly relative humidity and storage temperature, significantly impact the survival of the fungus in both seeds and soil (Dallagnol *et al*., 2011). Although *B. oryzae* can survive in both dry and moist soils, its longevity and pathogenicity are influenced by soil moisture levels. Several factors, including plant age, soil fertility, sowing practices, planting dates, temperature, moisture, and light, influence disease development. Rice plants are especially susceptible to infection during the dough and maturity stages. Early symptoms start as small lesions but become more prominent at panicle formation, with flowering and milk stages being particularly vulnerable (Ou, 1985).

A strong association has been found between nutrient-poor soils and higher brown spot incidence. Wang *et al*. (1980) observed an increased disease risk in soils deficient in silicon (Si), manganese (Mn), and potassium (K). Disease severity was negatively correlated with calcium (Ca), magnesium (Mg), potassium (K), and iron (Fe) content, as well as with K/N and Fe/Mn ratios, whereas higher levels of nitrogen (N), phosphorus (P), and manganese (Mn) correlated positively with disease susceptibility. Furthermore, nitrate-based nitrogen (NO_3^-) sources tended to enhance susceptibility more than ammonium-based (NH_4^+) sources (Imrani *et al*, 2014). Nitrogen application up to 180 kg/ha was reported to reduce foliar and stalk symptoms across different rice varieties. Fertilizer strategies, including the use of sulphur-coated urea, urea super granules, and combinations like neem cake with urea, substantially decreased brown spot severity. In nutrient solution trials, high potassium and nitrogen levels, or supplementation with zinc (Zn), manganese (Mn), or iodine, were effective in reducing disease severity. Conversely, excessive phosphorus, magnesium (Mg), nitrogen (N), and potassium (K) deficiencies, and the presence of cobalt (Co) and cadmium (Cd) aggravated disease severity (Ou, 1985). Higher nitrogen levels suppressed lesion enlargement, while silica application was effective in reducing the number of lesions. Fertilizer types and timing, particularly for phosphorus and potassium, also influenced disease outcomes (Singh *et al*., 2005). The application of iron ($FeSO_4$ at 25 kg/ha plus a 0.5% foliar spray) and copper ($CuSO_4$ at 1 kg/ha plus a 0.5% foliar spray) significantly reduced disease incidence. Silicon supplementation through calcium silicate (1.25 g/kg soil at the root zone) or potassium silicate foliar sprays (40 g/l) also yielded positive results (Rezende *et al*., 2009; Zanao *et al*., 2009). Holanda *et al*. (2002) reported that soils with high pH, low organic matter, and deficiencies in Fe, Si, Mn, and K, combined with low nitrogen and low cation exchange capacity, showed a higher prevalence of the disease. Among different seeding methods, drum seeding and line transplanting were associated with lower disease incidences compared to pre-germinated seed broadcasting or manual transplanting (Hegde *et al*., 2000). However, Jha *et al*. (2004) noted that direct seeding increased disease severity compared to transplanting. Long-term monitoring over five years indicated that zero-tillage in wheat had no significant impact on brown spot occurrence in subsequent rice crops (Singh *et al*., 2005).

Late sowing generally led to more severe disease compared to early sowing. Brown spot was largely absent during years with normal rainfall but intensified during dry seasons accompanied by heavy dew (Singh *et al*., 2005). Higher lesion densities were recorded when leaf wetness was prolonged. Successful conidial infection required a relative humidity above 89% and temperatures near 25°C, with free moisture on leaf surfaces significantly increasing infection success. The disease was most severe in dry soil, less severe in moist conditions, and least severe in flooded fields. Reports have also highlighted increased disease incidence and yield losses under rainfed and drought-stressed environments. Several grass and weed species serve as alternate hosts for *B. oryzae,* including *Echinochloa mexicana, E. colona, E. frumentacea, Imperata cylindrica, Leersia hexandra, Pennisetum typhoides, Panicum miliare, P. miliaceum, Digitaria sanguinalis, Saccharum officinarum, Zizania latifolia, and Cynodon dactylon*, among others (Ou, 1985).

Different methods of management of brown spot in rice

Host resistance

The most cost-effective method for controlling brown spot disease in rice is cultivating resistant varieties. Traditionally, breeding efforts have mainly targeted other major diseases like bacterial blight and blast (Savary *et al*., 2011). Nevertheless, the growing impact of brown spot now necessitates specific breeding strategies aimed at enhancing resistance. Accurate identification of resistant sources relies heavily on the use of dependable inoculation methods (Vu-Van and Sangchote, 2006). To boost disease visibility and obtain consistent evaluation results, researchers have suggested utilizing susceptible spreader lines alongside the test entries, applying conidial suspensions during the nighttime at the booting stage. Host-selective toxins produced by *B. oryzae* have also been explored as a means to screen resistant plants and calluses. Numerous investigations have been conducted to locate sources of resistance (Chakrabarti, 2001). For example, Satija *et al*. (2005) found that 15 out of 124 *Oryza sativa* entries displayed immunity (with less than 5% disease severity), whereas Hossain *et al*. (2004) reported only one resistant line among 29 tested entries. Field evaluations of upland rice germplasm, both indigenous and exotic, in eastern India indicated that several genotypes exhibited either full or partial resistance. Goel and Bala (2006) assessed 219 wild rice accessions from 15 Oryza species encompassing all six genomes and observed that 15 accessions were highly resistant, while 78 exhibited moderate resistance to brown spot. Another study involving 165 japonica and indica cultivars revealed that although 54 showed resistance at seedling, adult, or grain stages, only 22 demonstrated resistance at all three stages. Furthermore, cultivars like Swarna, BPT 1788, and MTU 1067 showed moderate levels of resistance during the stalk rot phase of the disease.

Five hybrid combinations, PBCMS 3A × Remi, PBCMS 3A × Madhav, PBCMS 3A × Pankaj, PBCMS 2A × Ranjit, and PBCMS 2A × IR 50, exhibited slight resistance to B. oryzae infection in grains (Singha *et al*., 2000), while Bora 15 stood out as notably resistant. Certain morphological attributes, including larger epidermal cells and a higher density of silicate cells, were found to contribute to enhanced resistance. Nevertheless, anatomical traits did not consistently align with resistance levels. It was noted that an increase in leaf angle tended to favour higher disease incidence, with narrower and upper leaves displaying reduced susceptibility. High-yielding, nitrogen-responsive cultivars appeared more prone to infection. Resistance often correlated with rapid physiological responses by the host, such as accelerated synthesis of polyphenols and their oxidized forms (Ou, 1985). Biochemical studies revealed that higher levels of phenolic compounds, lignin, flavonoids, silicon, and oxidative enzymes were associated with enhanced resistance, especially in cultivars like Giza 180. Although both resistant and susceptible cultivars experienced a decline in silicon and lignin content following infection, initial infection stages triggered a temporary increase in these compounds. Further observations showed that the second leaf was the most vulnerable to infection, while the youngest leaf exhibited the strongest resistance. Susceptibility was positively correlated with greater protein content, dry mass, total nitrogen, and free amino acid levels. On the other hand, elevated levels of non-reducing sugars and acid-hydrolysable polysaccharides were associated with resistance, while higher concentrations of reducing sugars promoted disease development. Reducing substances such as ascorbic acid and glutathione were also suggested to play a role in the resistance mechanism. A fungitoxic substance was synthesized within six hours of pathogen exposure, peaking at 72 hours, with the most active production phase occurring between 24 and 48 hours. Resistant varieties displayed a higher redox potential (Eh) when subject to nutrient imbalances or treatment with reducing agents like H_2S (Ou, 1985). Quantitative resistance against brown spot was reported in hybrid progenies resulting from crosses between susceptible cultivars (Pusa 44 and PR 114) and a resistant *Oryza nivara* accession (Goel *et al*., 2006). Genetic studies indicated that resistance was governed by dominant, additive, and epistatic gene actions. Sato *et al*. (2008) mapped three quantitative trait loci (QTLs), qBS11, qBS9, and qBS2, conferring resistance in the cultivar Tadukan, with qBS11 exerting the most significant effect. Later, Katara *et al*. (2010) identified ten QTLs linked to brown spot resistance, some of which may correspond to those previously reported by Sato *et al*. (2008).

Biological control

The use of antagonistic microbes, particularly commercial strains of Pseudomonas and Trichoderma, has proven effective in managing brown spot disease by competing for iron and essential nutrients, producing antibiotics, and directly attacking the pathogen. These beneficial microbes also enhance the plant's immune defence by inducing systemic resistance (Singh *et al*., 2005). Fluorescent Pseudomonas strains isolated from soil have been reported to lower disease incidence and inhibit fungal proliferation. Talc-based formulations containing Pseudomonas fluorescens have shown notable reductions in disease severity under experimental conditions (Joshi *et al*., 2007). Field trials indicated that *Bacillus megaterium*, at an ED_{50} of 1×10^3 cells/ml, completely suppressed *B. oryzae* growth and significantly decreased disease occurrence. Studies by Sarala *et al*. (2004) highlighted *B. subtilis* and *Trichoderma viride* as highly effective antagonists, while *T. pseudokoningii* was found to be particularly potent in promoting seedling vigour and germination (Krishnamurthy *et al*., 2001). Additionally, species of Trichoderma have been associated with enhanced nutrient uptake, increased biomass, improved root growth, and greater salt stress tolerance (Harman, 2011). Fungi such as *Cladosporium, Penicillium*, and *Aspergillus flavus* also exhibited strong inhibitory effects on the mycelial and spore development of *B. oryzae*. *T. viride* notably reduced mycelial expansion and spore germination by 63 and 77%, respectively, followed closely by *T. reesei* and *T. harzianum* (Harish *et al*., 2008). Application of a *T. harzianum*-based bioformulation resulted in a 55 to 58% decrease in seed-borne infection and mycelial growth. Seed treatments using *Trichoderma viride, T. harzianum,* and *Pseudomonas* spp. have achieved more than 70% disease suppression (Biswas *et al*., 2010; Joshi *et al*., 2007). Foliar application of *T. harzianum* has been shown to improve photosynthetic pigment concentrations, grain yield, and grain nutrient levels while lowering disease severity (Abdel-Fattah *et al*., 2007). Pre-treatment of rice plants with spore suspensions of *T. viride* and *T. harzianum* triggered elevated levels of phenolic compounds and soluble proteins, enhancing resistance against *B. oryzae* (Kumawat *et al*., 2008).

In Iran, field evaluations revealed that two *T. harzianum* strains efficiently controlled brown spot disease, and a *T. atroviride* strain promoted seedling development (Khalili *et al*., 2012). Moreover, antifungal compounds derived from

Fusarium graminearum strain F 402 provided over 80% disease control and completely inhibited *Cochliobolus miyabeanus* at 50 g/ml concentrations. Resistance in rice plants was markedly enhanced, with an 83–85% reduction in disease index when inoculated with an avirulent *B. oryzae* strain or treated with its culture filtrates. Organic amendments such as 20% goat dung and sheep urine also demonstrated effectiveness against brown spot (Selvi *et al*., 2008). Plant-derived substances have gained popularity for their antifungal activities. Extracts from *Artabotrys hexapetalus, peppermint, Piper nigrum*, and garlic significantly suppressed *B. oryzae* development. Leaf extracts from Juglans regia and Acorus calamus curtailed mycelial growth by 64% and reduced disease incidence by as much as 80% (Jitendiya Devi & Chhetry, 2013). Aqueous plant extracts, including those from *Spermacoce articularis, Leucas aspera*, and *Polygonum chinense*, prevented spore germination, while others inhibited germ tube elongation. Extracts from *Bixa orellana*, *Uvaria navum*, *Macaranga peltata* and Anacardium occidentale achieved complete inhibition of conidial germination. Furthermore, extracts from *Zornia gibbosa* and *Gliricidia sepium* effectively hampered germ tube development. Even at low concentrations (0.1%), garlic and Pithecellobium dulce extracts suppressed over 90% of mycelial growth (Raju *et al*., 2004). Among tested medicinal plants, *Thuja orientalis* extract demonstrated superior disease suppression and enhanced seed quality (Krishnamurthy *et al*., 2001). Methanolic extracts of *Prosopis juliflora* at 800 ppm completely inhibited mycelial expansion (Raghavendra *et al*., 2002). Water and ethanol extracts from leaves and oil extract from seeds of *A. indica* were found effective in reducing the radial growth of *C. miyabeanus* in culture and controlling the spread of brown spot in rice (Amadioha, 2002). Oil and extracts from *Azadirachta indica* leaves and seeds significantly curtailed disease spread. Essential oils from *Cinnamomum zeylanicum, Cymbopogon flexuosus*, and related aromatic plants displayed strong fungicidal properties. *Aphanamixis polystachya* seed oil restricted mycelial growth by up to 50% (Bhuyan *et al*., 2000). Extracts from *Curcuma longa, Solanum indicum,* and *Wrightia tinctoria* were also effective in preventing spore germination. Neem cake extracts achieved over 80% pathogen suppression, similar to the effects observed with castor, gingelly, and mahua cakes. Field trials have demonstrated that foliar applications of neem cake extract, *T. viride* and Nerium oleander leaf extract reduced disease severity by 70%, 53%, and 48%, respectively, along with yield enhancements (Harish *et al*., 2008). Commercial biopesticides such as Wan, Achook, Neemazal, Biotos and Tricure have also shown promising results in lowering disease severity and boosting yields. The antifungal efficacy of *Lawsonia inermis* was linked to the presence of lawsone (2-hydroxy-1,4-naphthoquinone). Extracts from *Adenocalymma allicea* completely inhibited *B. oryzae*, with its volatile oil demonstrating fungicidal and disease-suppressing properties. Secondary metabolites like mimosine from *Leucaena leucocephala* oils from *Citronella winterianus* and solamargine from *Solanum nigrum* effectively suppressed spore germination and germ tube elongation. Additionally, methanolic extracts and oils from plants such as *Ocimum gratissimum* and *Ocimum basilicum* have been reported to possess antifungal activity. Furthermore, non-traditional chemical agents, including calcium chloride, ferric chloride, and β-amino-n-butyric acid, when applied to rice foliage, were effective in inducing resistance. Chitosan treatments at 1000 ppm concentration achieved complete fungal growth inhibition (Rivero *et al*., 2008). Inducers of phytoalexins like DL-methionine, ferric chloride, cadmium chloride, sodium molybdate, and sodium malonate were successful in reducing brown spot severity. Among seed treatments, sodium molybdate and ferric chloride were notably effective in field conditions, while DL-methionine and nickel nitrate showed significant protection in pot trials. DL-methionine, 1AA, and sodium malonate offered strong defense against *C. miyabeanus* infections when applied to seedlings. Out of several tested metabolic enhancers, DL-methionine, DL-norleucine (10^{-1} M), and silver nitrate (10^{-2} M) exhibited 23 to 82% disease suppression rates. Phenolic compounds like resorcinol and phloroglucinol (10 mM concentrations) also effectively hindered pathogen development. Heavy metal salts such as nickel nitrate and sodium selenate managed to reduce stalk rot and leaf spot symptoms without causing significant phytotoxicity. Moreover, the application of abscisic acid (ABA), known to regulate ethylene responses, substantially enhanced rice plant resistance to B. oryzae. Similarly, the application of salicylic and benzoic acids, recognized for their antifungal effects, improved grain nutrient profiles while minimizing disease severity (Shabana *et al*., 2008).

Management through biocontrol agents

Law *et al*. (2017) emphasized that utilizing biocontrol microorganisms to manage plant pathogens is a preferred strategy because it is cost-effective, safe for human health, and eco-friendly.

Table 2 presents an overview of various biocontrol agents effective against *Bipolaris species*. The use of bacterial and fungal agents has gained popularity in plant disease management. Notably, Pseudomonas, Bacillus, and Trichoderma are among the most frequently employed antagonistic microorganisms due to their proven efficacy against numerous plant pathogens (Saravanakumar *et al*., 2007). Tamreihao *et al*. (2016) evaluated the potential of Streptomyces corchorusii strain UCR3 in suppressing rice diseases and promoting plant growth and yield. Similarly, Abdul-Fattah *et al*. (2007) demonstrated that *Trichoderma harzianum* is highly effective in pathogen control, and *T. viride* significantly reduced mycelial growth by 62.92% and spore germination by 77.03%. Moura *et al*. (2014) investigated seed treatments using bacterial strains like Bacillus sp. DFs418, *Pseudomonas synxantha* DFs185, P. fluorescens DFs223, and an unidentified DFs306, with DFs223 proving most successful in decreasing *B. oryzae* incidence. Manimegalai *et al*. (2011) also identified several fungal biocontrol agents, including *Penicillium antiheliums, P. chrysogenum, Aspergillus terreus, A. niger, A. sulphureus, A. fumigatus, A. flavus, Trichoderma viride*, and *T. harzianum,* that effectively inhibited pathogen activity. According to Nejad *et al*. (2014), among 20 actinomycete isolates, Streptomyces isolate G exhibited the strongest antagonism against *B. oryzae*. Further research by Tamreihao *et al*. (2016) reported the isolation of *S. corchorusii* UCR3-16 from the rice rhizosphere, which displayed antifungal activity against six major rice pathogens, including *B. oryzae*, through the

Table 2: Biocontrol agents used against *Bipolaris* spp

S. No.	*Biocontrol agent*	*Key findings*	*References*
1	Streptomyces corchorusii UCR3-16	Exhibited broad-spectrum antifungal activity against six critical fungal pathogens associated with rice cultivation.	Tamreihao *et al*., 2016
2	*Trichoderma harzianum*	Suppressed fungal mycelial growth by 65.33% in vitro and 64% under field conditions, confirming its potential as a biological control agent.	Gupta *et al*., 2013
3	Actinomycete isolates (20 strains)	Streptomyces isolate G demonstrated superior antifungal efficacy among tested strains against rice-associated pathogens.	Nejad *et al*., 2014
4	Bacillus sp. DFs418, P. fluorescens DFs223, *P. synxantha* DFs185, unidentified DFs306	DFs223 was identified as the most effective seed treatment agent for pathogen suppression.	Moura *et al*., 2014
5	*T. harzianum*	Enhanced seedling growth while substantially reducing infection rates in rice seedlings.	Moura *et al*., 2014
6	*Streptomyces philanthi*	Inhibited mycelial growth of phytopathogenic fungi, contributing to disease control.	Boukaew *et al*., 2013
7	*T. harzianum and T. viride*	Increased crop yield by over 70% and reduced brown leaf spot (BLS) disease incidence.	Biswas *et al*., 2010
8	*Penicillium chrysogenum, P. janthinellum, T. viride, T. harzianum, Aspergillus* spp.	Displayed strong antagonistic effects against multiple plant pathogens in in vitro studies.	Manimegalai, 2011
9	*Pseudomonas* spp.	Effectively reduced pathogen infection rates, enhancing plant health.	Ludwig *et al*., 2009
10	*Streptomyces vinaceusdrappus*	Significantly impeded fungal mycelial development in laboratory bioassays.	Ningthoujam *et al*., 2009
11	*T. harzianum*	Reduced pathogen spread and overall disease intensity in controlled environments.	Biswas *et al*., 2008
12	*T. viride*	Inhibited spore germination and mycelial growth by 63–77%, displaying notable antifungal activity.	Harish *et al*., 2008
13	*Pseudomonas* spp.	Significantly decreased disease incidence when applied as a biocontrol agent.	Joshi *et al*., 2007
14	*T. viride and T. harzianum*	Mitigated BLS disease severity through combined application.	Kumawat *et al*., 2008
15	*P. fluorescens*	Lowered disease occurrence and improved overall plant vigor under pathogen pressure.	Joshi *et al*., 2007
16	*T. harzianum*	Reduced mycelial growth by 62.92% and spore germination by 77.03% in experimental setups.	Abdul-Fattah *et al*., 2007
17	Six phylloplane microbial isolates	Demonstrated suppression of pathogen spore germination, minimizing initial infection events.	Harish *et al*., 2007
18	*Bacillus subtilis*	Prevented fungal mycelial expansion under in vitro conditions.	Sarala *et al*., 2004
19	*T. viride*	Achieved 77.03% reduction in spore germination and 62.92% inhibition of mycelial growth.	Harish *et al*., 2008
20	*Fusarium graminearum*	Displayed antagonistic activity against Cochliobolus miyabeanus, restricting its growth.	Ashiq *et al*., 2023
21	*T. pseudokoningii*	Reduced prevalence of BLS disease in infested rice crops.	Krishnamurthy *et al*., 2001
22	*T. viride*	Restricted mycelial development, confirming its antifungal potential.	Harish *et al*., 2007
23	*Bacillus megaterium*	Decreased severity of BLS disease under field application conditions.	Yu *et al*., 2025
24	*Pseudomonas fluorescens*	Lowered disease incidence, promoting healthier plant growth and improved yields.	Supraja *et al*., 2011

production of hydrolytic enzymes such as protease, chitinase, glucanases, and lipase. Boukaew *et al*. (2013) highlighted that *Streptomyces philanthi* suppressed mycelial growth of several rice pathogens via volatile organic compounds (VOCs), while *Streptomyces vinaceusdrappus* inhibited *B. oryzae* primarily through chitinase production (Ningthoujam *et al*., 2009). Additionally, rhizospheric Pseudomonas isolates were reported by Joshi *et al*. (2007) to effectively control *B. oryzae* and mitigate brown spot disease, with talc-based formulations of *P. fluorescens* yielding promising results. *Bacillus megaterium* was also shown to significantly lower brown leaf spot severity in field conditions, and *T. viride*, along with *Bacillus subtilis,* demonstrated strong antagonistic effects (Sarala *et al*., 2004). *T. pseudokoningii* further contributed to disease reduction (Krishnamurthy *et al*., 2001).

Harish *et al*. (2008) observed that among six phylloplane microorganisms tested, Cladosporium species markedly decreased spore germination and fungal growth of *B. oryzae*. *T. viride* alone reduced mycelial growth and spore germination by 63 and 77%, respectively. Moreover, bioformulations containing *T. harzianum* successfully decreased seed-borne infections and pathogen mycelial growth by 55 to 58%. Seed treatments with *Pseudomonas spp., T. viride* and *T. harzianum* led to yield improvements of up to 70% along with a substantial decline in disease severity (Joshi *et al*., 2007; Biswas *et al*., 2010). Foliar sprays of *T. harzianum* were found to lessen disease severity while enhancing photosynthesis and increasing carbohydrate and protein concentrations in rice leaves (Abdel-Fattah *et al*., 2007). Pre-treatment of rice plants with *T. viride* and *T. harzianum* spores offered protection against B. oryzae by elevating phenolic compound and soluble protein levels (Kumawat *et al*., 2008).

Khalili *et al*., (2012) confirmed that two strains of *T. harzianum* effectively controlled the disease in Iran, whereas a *T. atroviride* strain improved seedling growth. Furthermore, antifungal metabolites produced by *Fusarium graminearum* were able to control brown leaf spot caused by *C. miyabeanus* by more than 80%. Exposure of plants to avirulent pathogen strains induced resistance, resulting in an 83 to 85% reduction in disease severity. Pre-treatments with germinated spore fluids provided similar protection.

Management through mineral nutrients

Plants with insufficient nutrient supply are typically more prone to diseases compared to those that are well-nourished. Certain nutrients can improve a plant's ability to tolerate infections and reduce disease impact. Essential elements like nitrogen (N), phosphorus (P), manganese (Mn), iron (Fe), and calcium (Ca) significantly affect both the occurrence and intensity of plant diseases. For example, brown leaf spot (BLS) severity can increase with either a deficiency or an excess of nitrogen, although supplying nitrogen in the nitrate form rather than ammonium tends to alleviate disease symptoms. The phosphorus content in plant leaves also plays a crucial role in disease management, with optimal control of BLS occurring when leaf phosphorus levels are between 0.135 and 0.149%. Moreover, phosphorus availability influences the uptake of other micronutrients, indirectly affecting disease development. Singh *et al*. (2005) found that applying 48 kg/ha of phosphorus was ideal; exceeding this rate offered no further advantage and could even promote disease. Their findings also revealed a negative relationship between higher soil phosphorus levels and BLS incidence. In addition to its fundamental role in plant nutrition, potassium (K) supports the deposition of silica within plant tissues, physically restricting the formation of brown spots. Potassium also bolsters resistance through various mechanisms. According to Carvalho *et al*. (2010), elevated potassium and nitrogen levels delayed BLS symptom development and reduced the number of lesions. While nitrogen alone provided limited disease suppression, potassium notably increased phenolic compounds, which helped reduce both BLS and sheath blight severity. Similarly, the combination of iron and zinc showed beneficial effects in limiting disease progression (Prasad *et al*., 2010). Balardin *et al*. (2006) also demonstrated that potassium supplementation lessened disease severity in other crops, such as soybean rust. Furthermore, in the Guarani rice variety, higher potassium and zinc levels were linked to reduced blast disease severity, and potassium was shown to enhance resistance against *Helminthosporium sativum* in barley. Silicon (Si) has also been recognized for its role in strengthening plant defenses, particularly in reducing the severity of BLS in rice. A lack of zinc (Zn) has been associated with increased susceptibility to BLS. Minnatullah and Jha (2002) observed that zinc sulphate application led to significantly lower brown spot severity compared to other micronutrient treatments or untreated plots. They noted that applying 3 kg/ha of zinc, together with potassium (30 kg/ha), nitrogen (120 kg/ha), and phosphorus (30 kg/ha), effectively minimized both brown spot and sheath blight symptoms. Zinc is thought to enhance the plant's resistance mechanisms against foliar diseases such as leaf spots and mildew. Calcium (Ca) supplementation also impacted BLS intensity. The application of 30 ppm calcium was more effective in decreasing disease severity than 50 ppm. In the susceptible rice variety Benibhog, manganese (Mn) application at 5 to 10 ppm significantly reduced brown spot severity, indicating that adjusting manganese levels could markedly decrease disease incidence even in vulnerable cultivars. Several studies have confirmed negative correlations between brown spot infection rates and calcium or manganese uptake. Zanao *et al*. (2009) explored the impact of different silicon sources and application methods on BLS resistance in the Metica-1 rice cultivar. They compared soil and foliar applications of silicon from sources like wollastonite (calcium silicate), potassium silicate, and silicic acid. Their results indicated that soil applications were superior to foliar sprays in minimizing disease severity.

Management through plant activators

The use of plant activators, such as benzoic acid at a 20 mM concentration, has been shown to significantly reduce both the incidence and severity of diseases (Shabana *et al*., 2008). Applications of salicylic acid, benzoic acid, and hydroquinone have been reported to strengthen the plant's defense mechanisms against fungal infections caused by *B. oryzae* (Abbas *et al*., 2006). Among the various compounds tested, benzoic acid exhibited the highest level of effectiveness in both laboratory and greenhouse experiments. Likewise, sodium benzoate has been reported to successfully inhibit the growth of *Candida albicans* and *Geotrichum candidum* (Wen *et al*., 2016). In potato crops, the application of salicylic acid was found to not only delay the appearance of disease symptoms but also limit the advancement of Rhizoctonia infections (Hadi and Balali, 2010). Hydroquinone, known for its safety as an antioxidant, has also been effective in managing fungal pathogens transmitted through seeds (Elwakil and Metwally, 2000). Moreover, other compounds such as shikimic acid, jasmonic acid, and salicylic acid play important roles in activating plant immune responses, supporting both enhanced resistance and growth. These substances are involved in triggering the expression of defense-related genes as they translocate within plant tissues (Nino-Liu *et al*., 2006). Salicylic acid has been observed to stimulate the activity of phenylalanine ammonia-lyase (PAL), an enzyme associated with disease resistance, whereas jasmonic acid mainly contributes to promoting overall plant growth (Wen *et al*., 2005).

Disease management with fungicides

Various fungicides have been extensively evaluated in both laboratory and field conditions to assess their effectiveness in managing the pathogen responsible for brown spot disease in rice. Several potent inhibitors of fungal mycelial growth have been identified, including Kitazin, edifenphos, tridemorph, Foltaf, PP 296, Ridomil, Bitoxazol, Shield, triadimenol, Thiram, Hinosan, and Dithane M-45 (Arshad *et al*., 2013). Among the nine fungicides tested, hexaconazole (EC50 0.11 ppm a.i.) and propiconazole (EC50 0.42 ppm a.i.) exhibited the most significant inhibitory effects, followed by iprobenphos and edifenphos. Additionally, fungicides such as iprodione (Pereira *et al*., 2002), azoxystrobin, trifloxystrobin, and kresoxim-methyl have also been found effective in suppressing fungal growth. Research by Park and Cho (1972) found that fungicides such as Agallol, Rhizoctal, triforine, bitertanol, chlorothalonil, carbendazim, pyroquilon, tricyclazole, and mancozeb, when used in seed treatments, allowed some infection to persist in the endosperm. However, total elimination of the pathogen was achieved by immersing seeds for one hour in a guazatine and dichloromethane solution. Combinations of thiabendazole with maneb, iprodione with thiram, and thiram alone were particularly effective in eradicating *B. oryzae* from seeds (Coutinho *et al*., 2000). Other treatments, including sulphanilamide, griseofulvin, and seed soaking in compounds such as indole acetic acid, Na-pentachlorophenate, vitamin K3, and boric acid, significantly reduced lesion size (Ou, 1985). Foliar applications of aureofungin, edifenphos, and Dithane M-45 have also proven effective in controlling secondary infections caused by airborne spores. Disease control strategies reported by Ved *et al*. (2005) include seed treatment with tricyclazole (0.4%), three applications of Ridomyl MZ or Companion, and seed coating with thiram (2 g/kg). Field trials have suggested that foliar spraying is generally more effective than root dipping or seed treatment. Sprays with Bitoxazol, edifenphos, blasticidin SM, Shin-mel (phenyl mercury acetate), iprobenphos, propiconazole, sisthane and chlorothalonil all contributed to reducing disease severity.

Hexaconazole and propiconazole, when applied during the early booting and 50% panicle emergence stages, significantly reduced leaf spot and stalk rot, ultimately increasing grain yield. Similarly, mancozeb and edifenphos treatments showed comparable results (Lore *et al*., 2007). The combination of Brestan (fentin acetate) and Dithane M-45 during heading and grain maturity also resulted in good disease control. Antibiotics like Versicolin and Mycobacillin were found to be effective as foliar and seed protectants, respectively. Fungicides such as Tilt 25 EC and Armure 30 EC (both at 0.1%) also significantly reduced disease severity. Fungicide use has proven essential for managing disease outbreaks, particularly under changing environmental conditions. Qudsia *et al*., (2017) reported up to 10% disease reduction with Switch DF 80WG.

Kumar *et al*., (2017) tested Hexaconazole 25EC, Propiconazole 25EC, Carboxin 50WP, and Carbendazim 50WP, finding that propiconazole was highly effective, reducing fungal growth by 96.58% in vitro. In field trials, seed treatment with carbendazim (2 g/kg) and foliar spray with propiconazole (1 ml/L) resulted in a 37.26% reduction in disease severity and a 55.49% increase in yield (Sandeep, 2015). Bavistin (1500 ppm) was the most effective fungicide in suppressing fungal growth over a 144-hour incubation. Subsequent testing showed that propiconazole and hexaconazole were the most effective, with edifenphos and iprobenphos following closely behind. In field trials in 2010, mancozeb and edifenphos resulted in disease reductions of up to 86.2 and 78.7%, respectively, and yield increases of over 14%. Hexaconazole (2 mL/L) and propiconazole (1 mL/L) significantly lowered disease severity to 5.19% and increased productivity. Propiconazole at 250 ppm led to a nearly 97% reduction in fungal growth under laboratory conditions. Field trials on rice varieties Jaya PC-19 and Basmati-370 with seven fungicides showed that propiconazole reduced disease severity in three out of seven cases and increased yield in two. Iqbal *et al*. (2015) evaluated fungicides such as copper hydroxide (1250 g/ha), chlorothalonil + metalaxyl (750 g/ha), propineb (1250 g/ha), difenoconazole (313 ml/ha), and mancozeb (1250 g/ha), with copper hydroxide yielding the best results. Mustafa *et al*. (2013) tested new fungicides on the susceptible variety Super Basmati under high disease pressure and found Score (250 EC) at 308.2 ml/ha to be the most effective. Asghar *et al*. (2007) carried out field trials in Gujranwala, Pakistan, using fungicides and NPK macronutrients on Super Basmati rice. The combination of difenoconazole (315 mL/ha) and NPK (500 g/ha) resulted in a 9.31% reduction in disease severity and a 3.57 t/ha increase in yield. Shrestha *et al*. (2017) evaluated fungicides such as propiconazole 25EC (Tilt), carbendazim 50% WP (Bavistin), and carbendazim + mancozeb 63% (SAAF) on Sabha Mansuri rice. Propiconazole at 2 mL/L produced the lowest AUDPC (373.7), followed by SAAF and Bavistin. Yields of 5.22, 5.21, and 3.32 t/ha, respectively, were recorded. Fungicides like mancozeb and thiomal completely inhibited fungal growth at 150 and 200 ppm, respectively, while Melody Duo was less effective and Bavistin showed moderate success (Mohasin *et al*., 2025; Jatoi *et al*., 2019). Strobilurins, such as azoxystrobin, trifloxystrobin and kresoxim-methyl, along with iprodione (Pereira *et al*., 2002), also demonstrated high efficacy against *B. oryzae*.

Conclusion

The destructive brown spot disease, caused by *B. oryzae,* significantly affects rice crops globally, leading to notable losses in grain yield and characteristic brown lesions on leaves, ranging from circular to oval in shape. Despite progress in research, there remains a limited understanding of the host plant's resistance mechanisms to brown spot. Breeding programs must prioritize the identification of resistance sources and establish standardized diagnostic techniques for the disease. It is crucial to examine the epidemiological factors that contribute to the onset and spread of brown spot, as well as the origins and role of the primary inoculum. Furthermore, attention should be given to the physical factors influencing host plant physiology, which may exacerbate brown spot occurrences. Management approaches, including the use of fungicides, phytoextracts, nutrients, plant activators, and the development of resistant plant varieties, are essential for controlling the disease. An integrated management strategy that combines these methods offers the most effective approach to mitigate brown spot and its increasing threat to food security in the future.

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Authors Contributions

Author's Contribution: Dr. Mohd Rameez, Planning of the study, review and editing of MS.

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Conflict of Interests

The authors declare no conflict of interest.

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