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Advances in the Integrated Approach of Diseases Management in Case of Brown Leaf Spot Caused by *Helminthosporium oryzae*

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Abstract
Brown leaf spot caused by *Helminthosporium oryzae* (syn. *Bipolaris oryzae*) is a major fungal disease of rice causing yield loss and grain quality degradation in both irrigated and rainfed systems. Brown leaf spot is very severe in deficient soil nutrients, high humidity, continuous leaf wetness, and stressed environment. Chemical fungicides have been used traditionally for control of this disease but now the use of fungicide has become unsustainable owing to development of fungicide resistance, environmental pollution, and production cost. Integrated disease management (IDM) has thus become an effective approach for sustainable control of brown leaf spot disease. This review discusses recent developments in IDM of brown leaf spot through the integration of cultural, biological, chemical, and resistant host. Balanced fertilization, crop rotation, residue management, proper plant density, and irrigation schedule can minimize the incidence of this disease effectively. Use of resistant or tolerant rice cultivars has always been an economical approach. Systemic fungicide seed treatment and careful foliar application of contact and systemic fungicides prove to be an effective measure in disease management. Use of biological control agents like *Trichoderma* spp., *Bacillus* spp., and *Pseudomonas fluorescens* is proving successful through their ability to suppress pathogens and increase the plant's defense mechanism. Advances in molecular diagnostic methods, remote sensing, disease forecasting and models, and precision agricultural techniques can aid in early identification and control measures. Moreover, the use of integrated nutrient management, silicon supply, and plant growth promoting rhizobacteria can ensure good plant health and help build resistance against infection. The present review suggests that the combination of resistant varieties, proper nutritional status of plants, biological control agents, cultural measures, and need-based application of fungicides provides a sustainable, cost-effective, and environmental-friendly approach to disease management of brown leaf spot. Further work should be aimed at developing strategies of disease management resilient to climate change and the development of molecular breeding tools for long-lasting resistance.

Keywords: Brown leaf spot, *Helminthosporium oryzae*, *Bipolaris oryzae*, Integrated Disease Management, Rice, Biological Control, Fungicides, Host Resistance, Precision Agriculture.

1. Introduction
The brown leaf spot disease, which is caused by the fungus *Helminthosporium oryzae* (teleomorph: *Cochliobolus miyabeanus*; syn. *Bipolaris oryzae*), is one of the most ancient and economically damaging fungal diseases of the rice (*Oryza sativa* L.) crop. It can be found in almost all rice-growing areas across the globe, and is prevalent especially in the tropical and subtropical zones, as these environments provide ideal conditions for its development – high temperatures, humidity, long periods of wetting, and soil deficiency in nutrients. This disease is harmful to plants at all growth stages – from seedling through to mature plants, causing lesions on leaves, leaf sheaths, glumes, and grains. Historically, brown leaf spot became of international concern after the Bengal famine of 1943 when outbreaks of disease, along with unfavorable weather, led to significant reduction of rice harvests. Despite the introduction of modern farming practices that reduce the occurrence of epidemics, brown leaf spot still remains a serious problem for sustainable cultivation of rice, especially for low input systems, causing losses between 5% and 20%, while under favorable disease conditions and bad crop management yields can be reduced by more than 50%. Apart

from the yield reduction, brown leaf spot influences seed quality, germination, milling recovery, and market value of rice. Epidemiology of brown leaf spot is affected by the combination of many different factors – the host, pathogen, and environment. Imbalance of nutrients, especially nitrogen, potassium, silicon, and micronutrients deficiency, makes plants more susceptible to the infections. In the same way, the use of infested seeds, growing susceptible varieties of rice, monoculture, lack of field sanitation, and suitable weather make pathogens propagate. Conventional management strategies such as fungicide spraying have proven to be highly effective in suppressing the pathogen for the short term. Over-reliance on chemical fungicides is of concern since fungicide resistance, environmental pollution, fungicide residue buildup, and detrimental effects on other microorganisms are likely. Modern disease management programs focus on developing sustainable, environment friendly and cost-effective methods of managing plant diseases without over reliance on chemicals.Integrated Disease Management (IDM) is one way of achieving the objective through a combination of compatible disease management approaches such as planting disease free or resistant varieties, seed treatment, appropriate nutrition, biological control, cultural practices, forecasting and judicious use of fungicides. Developments in molecular diagnostics, remote sensing, precision agriculture, biological control using microbial agents, and genomics assisted breeding have greatly helped strengthen IDM by facilitating early disease diagnosis, monitoring and developing durable host resistance.This review will discuss the recent advances in the integrated management of brown leaf spot disease caused by *H.oryzae* (*Bipolaris oryzae*). The review will cover aspects such as biology of the pathogen, disease epidemiology and host-pathogen interaction and the recent developments in cultural, biological, chemical, genetic and digital disease management strategies.

2. Importance of Rice and Economic Significance of Brown Leaf Spot

Significance of Rice Crop and Economic Importance of BLSD

Significance of Rice: The rice crop (*Oryza sativa* L.) is one of the most important food grain crops in the world. Rice provides food for more than half of the world's population and is a vital crop in over 100 countries worldwide. More than 90 percent of world rice production is done by Asian nations. Rice is rich in carbohydrate, protein, vitamins, and minerals. In countries like India, China, Bangladesh, Indonesia, Vietnam, and Thailand, rice plays a crucial role in food security besides being an economically important crop. India is the second largest producer of rice globally and grows rice across different agro-climatic zones. Rice makes a significant contribution to the Gross Domestic Product of agriculture in India and helps thousands of farmers with its production, processing, transport, and marketing. Apart from being consumed by humans, rice products including bran, husk, and straw are used in animal feed, biofuel production, paper production, and in the cultivation of mushrooms. The rising demands for rice owing to population increase necessitates sustainable production and disease control.

3. Economic Importance of Brown Leaf Spot

Brown leaf spot disease is one of the earliest and most devastating fungal diseases of rice caused by *Helminthosporium oryzae* (syn. *Bipolaris oryzae*). This disease is common in all parts of the world where rice is cultivated and is more prevalent under conditions of deficient nutrients, drought stress, poor fertility of soils, and humid environment. The pathogen attacks the leaves, leaf sheaths, glumes, grains, and seedlings, and results in brown lesions that limit the photosynthetic surface area of the plants. This disease brings about yield reduction and poor quality of rice. Usually, yield losses due to this disease are estimated to be between 10-45%; however, sometimes the losses can be higher than 50% when there is severe epidemic and favorable environment. Poor grain filling, low seed weight, milling losses, and poor marketing value of the rice are also other damages caused by brown leaf spot. In the past, brown leaf spot was known in relation to the infamous Bengal famine of 1943 where disease incidences and poor environmental conditions led to significant reduction in rice yields. Even with better crop management techniques in the modern age, brown leaf spot still remains a problem in irrigated and rain-fed rice production systems. Brown leaf spot not only leads to losses in yields but also incurs extra costs to farmers in the form of chemical fungicides, seed treatment, resistant varieties, and proper management. Diseases cause reduction in quality, exportation and profitability for farmers especially where rice is the main cash crop. Variability in climate, constant rice cultivation, and emergence of fungicide-resistant populations of pathogens all exacerbate the economic burden caused by the disease. As such, the use of IDM practices that include the use of resistant varieties, quality seeds, proper fertilization, bio-control, cultural methods and rational fungicide application are key to sustaining rice productivity and food security while also boosting farmers' incomes.

4. Historical Background of Brown Leaf Spot Disease

Historical Background of Brown Leaf Spot Disease Caused by *Helminthosporium oryzae*

Brown leaf spot of rice disease is among the most ancient and economically valuable diseases affecting rice crops. It is caused by the fungus *Bipolaris oryzae*, previously known as *Helminthosporium oryzae* and later *Drechslera oryzae*. The disease has been acknowledged for more than a century already and has had a considerable effect on rice cultivation all around the world. The first descriptions of brown leaf spot date back to the end of the nineteenth and the beginning of the twentieth centuries, when scientists identified brown spots on rice plants' leaves in some Asian countries. In accordance with the fungus morphology, it was first categorized into the genus *Helminthosporium*. As taxonomic classification of fungi has improved, the pathogen was later transferred into genera *Drechslera* and finally *Bipolaris*. Brown leaf spot became widely known due to the 1942-1943 Bengal famine in India. An acute outbreak, poor crop management, bad weather conditions, wartime issues and food shortages led to enormous crop damage. From historians' and plant pathologists' perspective, this disease is one of the reasons that contributed to the reduction of rice crops during the famine. It has been spread across most parts of the world where rice is cultivated in Asia, Africa, America, and Australia. The infection is most destructive in soils with nutrient deficiencies, drought conditions, inadequate farm management, and hot, moist climates. Both upland and lowland rice systems can get affected by this fungal disease.In recent decades, the process of learning about the disease cycle, biology, epidemiology, and the interaction between the pathogen and host plants has progressed remarkably. Scientists have found out how infected seeds, crop residue, and wind-blown spores spread the fungus. Through plant breeding techniques, scientists have developed more resistant rice varieties, while integrated disease management programs have gained acceptance using tolerant varieties, appropriate fertilization, agricultural practices, biocontrol agents, seed treatment, and limited fungicide application. Modern studies based on molecular biology and genomics have provided more insights into *Bipolaris oryzae* that have helped in accurate pathogen identification, better disease monitoring, and environmentally safe management of this disease. Present day studies focus on IDM, precision farming, and crop production resilient to climate change.

5. Morphology and Identification of *Helminthosporium oryzae*

The fungus causing brown leaf spot disease of rice is the species known as *Helminthosporium oryzae* (*Bipolaris oryzae*). *Helminthosporium oryzae* belongs to the phylum Ascomycota, class Dothideomycetes, order Pleosporales, and family Pleosporaceae. This fungus survives in infected seeds, plant residues, and on other grasses acting as its major inoculum source for the next rice-growing season. In cultures, the fungus forms colonies with white-greyish appearance in the beginning and becoming dark olive and even black as a result of numerous sporulation processes. Mycelium is septate, branched, and olive-brown. Conidiophores occur singly and in small clusters, being straight or slightly curved, brown, septate, and producing conidia on their apexes. Conidia are long, cylindrical and slightly curved, smooth-walled, light- to dark-brown, with 5-10 transverse septa. The fungi are estimated to be about 60-150 µm long and 12-18 µm wide with bipolar germination (germination from both ends) being an identifying feature of this particular group, *Bipolaris*. The fungi can be identified using various factors including disease symptoms, observation under microscope, isolation on PDA (potato dextrose agar), and use of molecular methods such as PCR (polymerase chain reaction) and DNA sequencing of the ITS (internal transcribed spacer) region. Identification of *Bipolaris oryzae* is crucial for disease detection, epidemiology, and disease management.

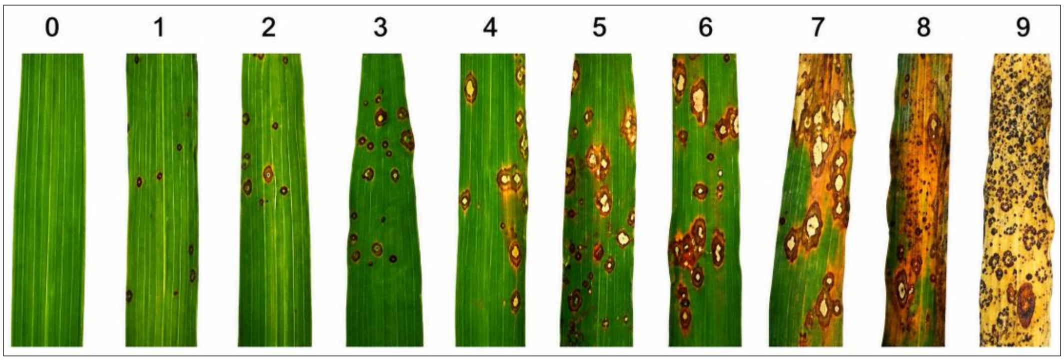

Fig 1: Scale for the scoring of brown leaf spot of Rice

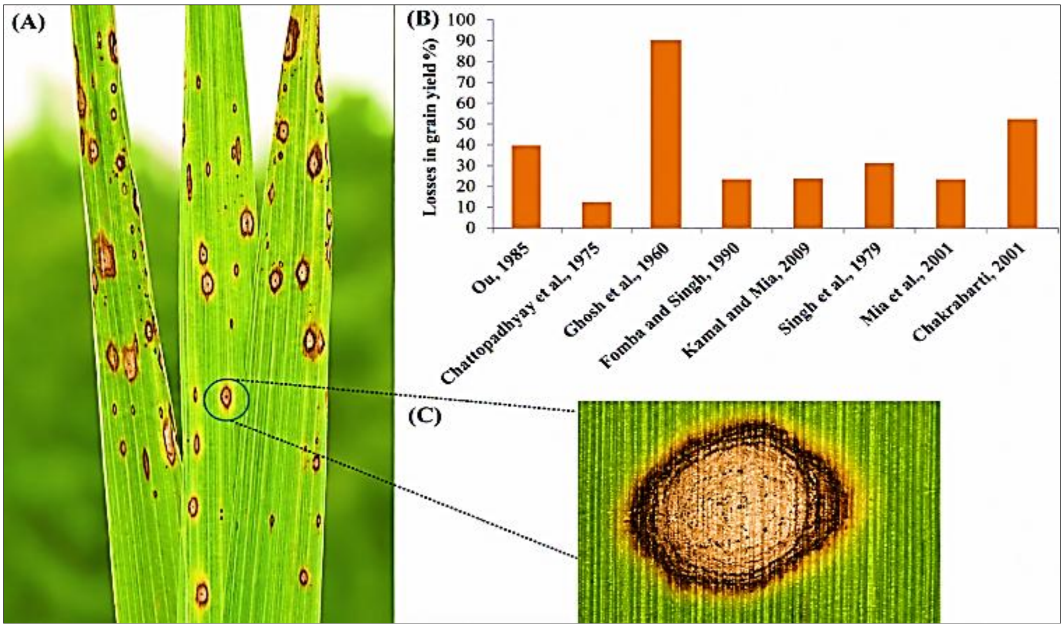

Fig 2: Morphology and Identification of *Helminthosporium oryzae*)

The disease cycle of brown leaf spot disease induced by *Helminthosporium oryzae* (also known as *Bipolaris oryzae*) starts from the survival of the fungus in infected seeds, crop residues, volunteer rice plants and also some species of grasses. Seed-borne inoculum is the major source of primary infection that enables the fungus to survive between successive cropping seasons. In the presence of favourable conditions like temperature of 25 to 30°C, relative humidity more than 90%, leaf wetness for long duration and also heavy rainfall, abundant conidia formation occurs on infected plant parts. Conidia are disseminated by wind, rain splash, irrigation water, insects and also by farm equipment to healthy rice plants. After reaching on the surface of the leaves, the conidia germinate and infect the plant by penetration mostly through cuticle, stomata and wounds. The infection causes formation of small brown spots that increase in size to form circular to elliptical spots having grey to light brown centre and dark brown borders. Conidia production takes place in these lesions causing the repeated cycles of secondary infection. The pathogen multiplies at a fast rate in periods of constant humidity and becomes more pronounced in crops which are lacking nutrients like nitrogen and potassium, or when the crops have been exposed to stress factors like drought. Towards the end of the growing period of the crop, the fungus survives in seeds, straw, and crop residue, thus forming the main inoculum for the following rice planting season. Knowing the disease cycle is very important in developing IDM, since activities like using clean seeds, crop residue disposal, proper fertilizer application, growing resistant cultivars, using bio-control agents, and applying fungicides at the appropriate time are capable of breaking the life cycle of the pathogen.

7. Epidemiology

Brown leaf spot disease of rice, caused by *Helminthosporium oryzae* (presently referred to as *Bipolaris oryzae*), is a disease that spreads through infected seeds and residues and which occurs in most regions in the world where rice is grown. The fungus survives during off-season periods in infected seeds, residues, volunteer plants, and certain grasses. Seeds of the fungus act as primary inoculum while airborne spores on infected tissues act as secondary inoculum. Infection occurs in all growth stages of rice from seedling stage to mature grain. But the severity of infection increases during tillering, booting and grain filling stages.

Environmental conditions are very important in the development of this disease. Warm temperature of 25-30°C, high relative humidity (>85%), presence of dew, continuous rain, leaf wetness, cloudy days are favorable for infection. The pathogen has the greatest impact in low input and rain-fed cultivation systems where there is the problem of deficiency in nutrients such as nitrogen, potassium and silicon. Other factors such as drought, poor soil fertility, acidic soils and inappropriate management practices predispose the hosts and facilitate disease outbreaks. The disease starts when the fungal spores germinate on the wet leaf surfaces. The germ tubes will penetrate either directly or through natural openings in the host plants resulting in lesion development. In favorable conditions, new spores are formed from the lesions after a few days, thus causing reinfection of the crops throughout the season. The factors that help in dispersal of the pathogens include wind, splash by rain, irrigation water, farm implements and planting materials that are already infected. Pathogen outbreaks depend on a susceptible variety of rice, a virulent population of the pathogen, and a conducive environment; the process is generally known as the disease triangle. Climate variability such as increased humidity, inconsistent rain and temperature changes in the climate due to climate change has contributed to an increase in the number of outbreaks of brown leaf spot in different parts of the world where rice is grown. The study of the disease epidemiology is important in the prediction of disease outbreaks and disease management strategies.

8. Symptoms and Disease Diagnosis

Leaf blight, which is caused by *Helminthosporium oryzae* (now known as *Bipolaris oryzae*), is one of the most common fungal diseases of rice, affecting the crop during all growth stages from the seedling stage to the mature stage. Leaf blight is a foliar disease that occurs on the leaves, leaf sheath, culms, glumes, and grains. Symptoms of this disease cause serious grain yield losses and poor grain quality. Initially, small, circular to oval dark brown lesions appear on the leaves. These lesions develop into oval and elliptical spots having grayish or light brown centers and dark reddish-brown margins. In case of severe disease occurrence, the lesions join together to create leaf blights that cause early leaf blighting and drying of the leaves, resulting in lower photosynthesis efficiency. Leaf blight may cause blighting of the seedlings with weak plants. Panicles and grain infection may lead to grain discoloration, poor grain filling, poor seed germination, and poor milling quality. Disease development is favored by warm temperature (25-30°C), high humidity, long period of leaf wetness, deficiency of nutrients in the soil, and use of infected seeds. Plants with deficiency of nitrogen, potassium, silicon, and other important elements are generally more vulnerable to disease attack. The disease tends to be more serious in rainfed and stress prone environment. Disease diagnosis for brown leaf spot disease is done through field, laboratory and molecular diagnostics. Field diagnosis is achieved through visualizing typical symptoms of brown lesions with grey centers and dark margins. Plant tissue from the affected leaves is collected and cultured in media like potato dextrose agar (PDA). Septate brown mycelium, brown conidiophores, and elongated multi-cellular conidia with 5-10 transverse septa that germinate from either end of the cell are some characteristics of *Bipolaris oryzae* fungus. Modern molecular diagnostic techniques such as polymerase chain reaction (PCR), quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP) and ITS DNA sequencing have been used to identify the pathogens rapidly and with very high precision. Some recent development in disease diagnosis include use of remote sensing, drone-based images, hyperspectral image analysis, artificial intelligence (AI) and machine learning techniques.

9. Environmental Factors Influencing Disease Development

The incidence and severity of brown leaf spot disease are affected to a great extent by the environment. Weather, soil fertility, and cultural practice determine the conducive environment that results in infection, survival, and dissemination of the disease pathogen. Knowledge of these environmental variables is necessary for designing IDM systems. One of the most important of such factors is temperature. At temperatures ranging from 25°C to 30°C, the pathogen causes infection to the host plant easily. High temperatures lead to rapid growth of the fungus and germination of its spores as well as development of lesions on the infected leaves. Incidence of the disease is reduced when temperatures are either low or very high.

Relative humidity and leaf wetness are other critical factors that influence the occurrence of the disease. When relative humidity levels are above 85%-90%, and leaves are kept wet for 8-12 hours, there are favorable conditions for disease development. Dew, rain, fog, and water used for irrigation make it possible to infect the plants with the disease-causing fungus. Soil fertility is another important factor affecting the development of brown leaf spot. The more the soil is poor in nitrogen, potassium, silicon, or other essential elements, the more it makes rice susceptible to infection. Potassium and silicon provide the strength to plant cell walls and resistance, while nutrient-poor plants become weak and thus become more susceptible to the invasion of fungi. Over-usage of nitrogen can also exacerbate this problem as it will produce lush leaves. The crop residue and infected seed are the main sources of inoculums. The fungus will live in infected straw, stubble, volunteer rice and infected seeds. This will result in the persistence of disease through the seasons, especially when there is no crop rotation between seasons. Plant stress, whether due to drought, waterlogging, salinity, poor drainage, or even insect damage, predisposes the rice plant to infection. All such stress conditions make it easy for the fungus to infect the plant. This is because stress weakens plant resistance to disease. Overcrowded planting can also predispose the plant to the disease. Climate change is expected to influence the epidemiology of brown leaf spot by altering temperature, rainfall patterns, and humidity. Increased frequency of extreme weather events and prolonged periods of high humidity may increase disease incidence in many rice-growing regions, emphasizing the need for climate-resilient disease management strategies. Overall, the interaction between favorable environmental conditions, susceptible rice varieties, and the presence of *H. oryzae* determines the occurrence and severity of brown leaf spot disease. Monitoring weather conditions, maintaining balanced crop nutrition, improving field sanitation, and adopting integrated disease management practices are essential to minimize disease development and protect rice yield.

10. Yield and Quality Losses

Brown Leaf Spot (caused by *Helminthosporium oryzae* (*Bipolaris oryzae*) is considered one of the most devastating fungal diseases of rice resulting in considerable decrease in grain yield and quality of the rice. This fungal disease attacks the rice at various stages from its early vegetative stage through to its maturation stages by causing brown oval to circular lesions on leaves, leaf sheaths, glumes, and grains. It causes a decrease in the effective area for photosynthesis leading to poor growth, poor tillering, poor panicle formation, and poor grain filling resulting in grain yield losses of about 10-30% but more than 50% in some cases especially where there is nutrient deficiency, susceptibility of cultivars, and humid conditions. Apart from yield loss, brown leaf spot causes a deterioration in the quality of the grains. Grains become discolored, shriveled, lightweight, and poorly filled making them have low thousand-grain weight and milling recoveries. Discoloration makes them lose their market value and consumer appeal and even affects seed quality through decreasing germination rate and vigor. Infected seeds are also another important source of inoculum that helps to spread the disease into the next season. In addition to this, the disease also decreases the nutritional value of the rice crop because of reduced carbohydrates synthesis in the crop. The other factors responsible for increasing the disease severity are the deficiency of nutrients like nitrogen, potassium, and silicon, in addition to drought or moisture stress. As such, it is important to have efficient disease management through IDM in order to avoid losses from yield and quality.

11. Host and Pathogen Interaction

The interaction between rice plants and the *Helminthosporium oryzae* (*Bipolaris oryzae*) is a complicated biological event which involves the strategies of infection by pathogens and the defense mechanism of the host. Infection occurs in favorable environmental conditions, especially high levels of humidity, long duration of leaf wetness and temperature ranging from 25–30°C. The conidia germinate and form germ tubes that invade the host through stomata or epidermis using mechanical pressure and cell wall-degrading enzymes, like cellulases and pectinases. These enzymes play an important role in the infection because they degrade the plant cell wall and enable rapid invasion of leaf tissues. Once the pathogen enters into the host, it secretes phytotoxins and enzymes which damage plant cells leading to the appearance of brown lesions characterized by gray or light colored centers and dark brown margins. As a result, the fungus absorbs nutrients from infected tissues, leading to the development of chlorosis, necrosis, inhibition of photosynthesis, leaf senescence and poor grain filling. Rice plants have some defense responses to defend against the pathogens. The first level of defense is the presence of physical barriers such as cuticles and cell walls, and then there comes the biochemical response. In the event of pathogen recognition, rice plants activate pattern-triggered immunity (PTI) and release ROS, phytoalexins, and PR proteins. There is an induction of defense enzymes like peroxidase (PO), polyphenol oxidase (PPO), phenylalanine ammonia-lyase (PAL), and chitinase which help in cell wall reinforcement and growth inhibition of fungi. Resistant rice varieties have shown faster and strong defense responses compared to susceptible rice varieties.The outcome of this interaction depends on several factors like the environment, host genetics, virulence of pathogens, and crop management strategies. Nutritional deficiency such as silicon, potassium, and excess fertilization with nitrogen make the host more susceptible to pathogen infection. On the other hand, proper fertilization, resistant varieties, use of biocontrol agents, and fungicide applications increase the defense responses of the host. Several rice resistance (R) genes, quantitative trait loci (QTLs), and signaling pathways involved in regulation of rice defense mechanism against *H. oryzae* including SA, JA, and ET have been identified through molecular analysis.

12. Conclusion

Brown leaf spot of rice disease, caused by *Helminthosporium oryzae* (*Bipolaris oryzae*), remains one of the most economically significant fungal diseases of rice cultivation. Brown leaf spot of rice reduces yield and the quality of grains and decreases overall productivity of the crop depending upon nutrient insufficiency, moisture stress, and improper crop management. The conventional practice based only on the usage of fungicides is not always enough because of environmental issues, higher expenses, and fungicide resistance.The integrated disease management (IDM) practice represents the most effective and sustainable way of brown leaf spot disease management. It involves the usage of resistant rice variety, the usage of certified disease-free seeds, seed treatment with proper fungicides or biological agents, correct nutrient management, correct irrigation, crop rotation, field sanitation, and proper fungicide application after disease monitoring. The use of biological control agents like *Trichoderma* spp., *Pseudomonas fluorescens*, and *Bacillus* spp. increases the efficiency of disease management and reduces the usage of chemical fungicides. The recent breakthroughs in molecular diagnostics, remote sensing, precision agriculture, forecasting techniques, and genomics-based breeding have greatly aided the identification and management of this disease. The innovations allow farmers to take appropriate and timely action measures which reduce crop damage and promote sustainable rice cultivation. The future research must target the development of resistant varieties, improvement of bio-control measures, variability in pathogens, and climate-smart disease management techniques. Awareness among farmers and the support of policies would be key to the success of the management approach.On the whole, the combined efforts of cultural, biological, chemical, and technological management of brown leaf spot disease caused by *Helminthosporium oryzae* ensure an environment-friendly, economically viable, and sustainable disease management. This integrated approach would play a crucial role in ensuring sustainable rice production and food security.

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