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Review Article

Managing Wheat Blast: A Call for Coordinated Genetic, Chemical, and Quarantine Interventions

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ABSTRACT

Wheat blast is a highly destructive disease that has emerged as a significant challenge to wheat production in warm and humid regions, caused by the fungal microorganism *Magnaporthe oryzae* pathotype *Triticum* (MoT). The disease was first reported in Brazil in 1985, spread across South America and has been identified in Asia (Bangladesh and India) and Africa recently (South America, including Bolivia, Paraguay, and Argentina) raising concerns worldwide. This review summarizes the epidemiological development, transcontinental distribution, and phytosanitary implications of wheat blast, highlighting the urgent need for coordinated international surveillance, breeding for resistance, and strict seed health protocols to inhibit global incursions. Since its initial outbreak in Brazil, the pathogen has demonstrated a capacity for rapid transboundary spread and severe yield losses. Its recent emergence in South Asia has intensified concerns, prompting surveillance efforts in Pakistan. Encouragingly, recent findings indicate that major wheat-producing regions in the country remain free of the disease. Nonetheless, the potential for regional spread remains a significant concern. Despite the grave implications for agricultural productivity, food security, and rural livelihoods, wheat blast has historically received limited attention at the global level. If left unmanaged, it could lead to widespread socio-economic disruption, including food insecurity and rural displacement. This article outlines a proposed framework for managing the threat through an integrated disease management (IDM) approach. Key components include the development of genetically resistant cultivars, prudent fungicide application, strict phytosanitary measures, and enhanced international collaboration to curb transboundary movement. A holistic, science-led strategy—underpinned by genomics-assisted breeding, robust surveillance, and coordinated global policy responses—is essential to safeguard wheat-based food systems in both endemic and at-risk regions.

Keywords: Wheat Blast, *Magnaporthe oryzae* pathotype *Triticum* (MoT), IDM, Genetic Resistance, Wheat Blast Hot Spots, Epidemiology.

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INTRODUCTION

The rapid growth of the population has placed record pressure on agricultural systems to enhance food production and meet intensifying nutritional stresses. (Afzal et al., 2021a). Among staple cereal crops, wheat (*Triticum aestivum* L.) plays a pivotal role in global food security due to its adaptability to diverse agroecological zones, long shelf life, and versatility in food processing (Dixon et al., 2009; King et al., 2024; Afzal et al., 2024). Wheat contributes extensively to caloric intake and rural livelihoods, particularly in low- and middle-income countries where it forms the base of both subsistence and market-oriented farming systems (FAO, 2021).

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Wheat accounts for the leading share of global crop trade, beyond the collective trade volume of all other crops (Chatrath et al., 2007; Afzal et al., 2015; Afzal et al., 2021b), serves as a staple source of nutrition and a valuable raw material for multiple industrial applications (Islam and Gupta, 2025) Nevertheless, Nevertheless wheat production is under threat from a range of biotic stresses, particularly fungal pathogens (Mushtaq et al., 2025; Afzal et al., 2022; Afzal et al., 2018).

Wheat cultivation has long been challenged by persistent and economically devastating diseases such as rusts, Fusarium head blight, and Septoria leaf blotch, which comtinue to pose significant threats to international food security and crop productivity (O'Driscoll et al., 2014). Wheat blast, or "brusone," is an emerging fungal disease of global concern caused by *Magnaporthe oryzae* pathotype *Triticum* (MoT), a member of the *M. oryzae* species complex (syn. *Pyricularia oryzae*). Despite its economic and epidemiological significance, wheat blast has received insufficient global attention and has never been addressed in terms of aggressiveness. The narrow base of genetic resistance, lack of durable cultivars, and underdeveloped forecasting systems have hindered effective mitigation. Therefore, an integrated approach that combines host plant resistance, predictive modeling, agronomic optimization, quarantine enforcement, and targeted fungicide use is essential for long-term disease management.

This article presents a comprehensive review of wheat blast, focusing on its global distribution, biological etiology, and the agro-economic ramifications of its outbreaks. It also critically examines the progress in resistance breeding, highlights the significance of epidemiological modeling in disease forecasting, and outlines current and emerging strategies for disease suppression under an Integrated Disease Management (IDM) framework. Emphasis is placed on identifying research gaps and proposing strategic directions to enhance resilience in wheat production systems and mitigate the risk of future epidemics under the changing climate and evolving trade dynamics.

Economic significance of wheat blast

The economic implications of wheat blast are profound, affecting both on-farm income and regional grain markets, and threatening food and nutritional security. Since its first outbreak in Brazil in 1985 (Igarashi et al., 1986), the disease has expanded its geographic footprint to other parts of South America, including Bolivia, Paraguay, and Argentina. This spread has been documented in various studies (Ceresini et al., 2019a; Tembo et al., 2020; Surovy et al., 2023), highlighting the disease's progression across the continent and more recently to South Asia, with the first confirmed occurrence in Bangladesh in 2016 (Islam et al., 2016). The genetic identity and origin of the wheat blast pathogen have been traced to a South American lineage of *Magnaporthe oryzae* Triticum (MoT) (Callaway, 2016; Islam et al., 2016), and it is believed to have spread from South America to Bangladesh and Zambia through international wheat trade (Hoque et al., 2023). The epidemic in Bangladesh during 2016 caused damaged in the range 20-100% in different zones (Islam et al., 2016).

Rapid dispersal and high epidemic potential have significantly curtailed expansion of area under wheat cultivation in the Cerrado and other savanna agro-ecologies, with over three million hectares affected by the early 1990s (Barea and Toledo 1996;Ceresini et al., 2018). Wheat blast is a highly destructive disease capable of causing total crop failure and severely compromising grain quality during epidemic outbreaks (He et al., 2021). During the initial phase the outbreak of disease damaged produce 100% even (Valent et al., 2021; Singh et al., 2021a). The severity of damage depends largely on the timing and extent of infection, with pre-anthesis or early anthesis infections often resulting in total spike sterility and grain abortion (Goulart and Paiva, 1992). In contrast, infections during grain filling produce small, shriveled, and lightweight grains, often unfit for human consumption (Malaker et al., 2016; Urashima et al., 2009). The extent of damage caused by wheat blast is strongly influenced by the crop's phenological stage at the time of infection, the susceptibility of the host genotype. Wheat blast most severely affects the crop when the spikes are infected, particularly around the flowering stage. While the fungus can also attack leaves and other green parts, such infections are less common and cause less damage. The risk of infection increases in warm, humid conditions, especially when the wheat florets are open and exposed. The most severe agronomic losses typically occur when infection coincides with anthesis or the early grain-filling stage—critical periods for reproductive success and grain set. Infected grains become misshapen, desiccated, and exhibit a significantly reduced thousand-kernel weight (TKW), thereby diminishing both marketability and viability. These compromised grains are often discarded during post-harvest processes such as threshing and winnowing due to their poor physical characteristics (Goulart et al., 2007). The pathogen's ability to rapidly adapt and spread under favorable environmental conditions underscores the urgent need for integrated disease management strategies and the development of blast-resistant cultivars.

Etiology

Wheat blast is caused by a distinct pathotype of *Magnaporthe oryzae*, designated as the *Triticum* pathotype (MoT)

(Singh et al., 2021a). This pathogen is a haploid, filamentous ascomycete fungus classified taxonomically within the phylum Ascomycota, class Sordariomycetes, order Magnaporthales, and family Magnaporthaceae (Couch and Kohn, 2002; Dostart, 2022). While M. oryzae is widely recognized for its pathogenicity on rice, the MoT pathotype demonstrates strict host specificity for wheat and is genetically distinct from the rice-infecting lineages. This genetic divergence underscores its independent evolutionary lineage and host adaptation, which has significant implications for disease management and surveillance in wheat production systems.

Morphology and reproduction

Wheat blast has been a significant threat to wheat cultivation since the 1980s, particularly in South America, and its biology remains poorly understood (Islam et al., 2023). The pathogen is known for its production of septate, branched hyphae and reproduces asexually via conidiogenesis, producing pyriform (pear-shaped) 2-septate conidia borne sympodially on geniculate conidiophores. The conidia are hyaline to pale brown and serve as the primary dissemination propagules. These are pyriform (pear-shaped), 3-septate spores that serve as the primary means of infection (Curz and Valent, 2017). The teleomorphic stage of the fungus is classified within the Pyrenomycetes, characterized by the production of predominantly four-celled ascospores contained in unitunicate asci that are irregularly arranged within long-necked perithecial ascomata (Cruz and Valent, 2017). *Magnaporthe oryzae*, the causative agent of rice blast disease, exhibits a hermothallic reproductive system, meaning individual strains possess both mating-type idiomorphs. However, these strains are self-incompatible, necessitating outcrossing for sexual reproduction. Mating compatibility in *M. oryzae* is regulated by the mating-type (MAT1) locus, which exists in two distinct forms, MAT1-1 and MAT1-2. Successful sexual reproduction occurs only between strains carrying opposite alleles at this locus. This genetic mechanism ensures genetic recombination and variability in populations, which has significant implications in agronomy for the evolution of pathogenic races, potential resistance breakdown, and the development of durable disease management strategies (Kang et al., 1994; Saleh et al., 2012).

Sexual reproduction has not been observed in the *Magnaporthe oryzae* population infecting wheat (*Triticum aestivum*), indicating that this pathotype follows a predominantly anamorphic life cycle. The absence of a teleomorphic stage in field populations suggests that genetic variation in wheat-infecting isolates arises mainly through asexual reproduction, mutation, and possibly parasexual recombination, rather than meiotic recombination. This reproductive mode limits genetic diversity but may also facilitate the rapid clonal expansion of virulent races under field conditions, posing significant challenges for resistance breeding and integrated disease management (Farman et al., 2017).

Genetic diversity and pathogenicity of *Magnaporthe oryzae* pathotype *Triticum* in wheat

Although closely related to *M. oryzae* pathotype *Oryza* (MoO), which causes rice blast, MoT is genetically distinct and host-specific to wheat (Hossain, 2022). High genetic variability and adaptability in the MoT genome contribute to epiphytotic outbreaks, particularly under conducive agroclimatic conditions. There is evidence of high mutation and recombination potential in its genome, contributing to pathogenic variability and fungicide resistance. MoT exhibits strict host specificity, primarily infecting wheat and closely related cereals (e.g., triticale, barley, durum wheat), while showing no cross-infectivity with MoO (rice pathotype), reflecting genetic and pathogenic divergence (Prabhu et al., 1992; Tosa et al., 2004). Phylogenomic analyses indicate that *M. oryzae* isolates infecting wheat (pathotype Triticum), rice (pathotype Oryza), finger millet (pathotype Eleusine), turfgrass (pathotype Lolium), and foxtail millet (pathotype Setaria) are genetically well-defined, forming distinct pathotype groups. Each pathotype shows limited pathogenicity on non-host species (Makaju et al., 2016; Gladieux et al., 2018), which explains why the Triticum pathotype is not capable of causing disease in rice. Host specificity is determined by effector proteins that suppress host immunity (Inoue et al., 2021).

Mechanisms of infection

The infection process of MoT begins when spores land on wheat spikelets, particularly during flowering. Under warm, humid conditions, the spores germinate and form germ tubes that adhere to the plant surface. A specialized structure called the appressorium then develops, generating high pressure to penetrate the plant cuticle. Once inside, the fungus colonizes plant tissues, initially avoiding cell death (biotrophy) before switching to a necrotrophic phase that kills host cells.

MoT releases effector proteins to suppress the plant's immune responses, allowing further spread within the tissues. After extensive colonization, the pathogen produces new spores on infected tissues, which are dispersed by wind or rain, causing further outbreaks. These efficient infection strategies enable MoT to rapidly cause wheat blast epidemics under favorable environmental conditions.

Host defense responses

Wheat defends itself against MoT through a layered system involving physical barriers, immune recognition, signal transduction, and expression of antimicrobial compounds. However, MoT's secretion of effectors often suppresses these responses, especially in susceptible genotypes, highlighting the importance of breeding for durable resistance.

Symptomology of wheat blast

Wheat blast primarily targets the reproductive structures of the plant (spikes), resulting in characteristic premature bleaching known as the "whitehead" symptom. Affected spikelets typically exhibit floret sterility, leading to partial or complete grain loss. The severity of damage depends largely on the timing and extent of infection, with pre-anthesis or early anthesis infections often resulting in total spike sterility and grain abortion (Goulart and Paiva, 1992). In contrast, infections during grain filling produce small, shriveled, and lightweight grains, often unsuitable for human consumption (Urashima et al., 2009).

Symptomatology varies depending on the infected plant organ, leading to disease nomenclature such as leaf blast, spike blast, node blast, collar rot, or rotten neck blast (Saharan et al., 2016). The disease typically initiates as isolated foci in a field, which coalesce under conducive conditions, resulting in epiphytotic outbreaks. The most diagnostic symptom is the bleaching of the spike, beginning at a blackish-gray necrotic point near the rachis or peduncle, where vascular occlusion interrupts assimilate translocation to distal spikelets In severe cases, multiple necrotic points are observed along the rachis, especially in susceptible genotypes under high inoculum pressure (Cruz and Valent, 2017).

Partial or complete bleaching of spikes is the hallmark symptom, usually beginning from a distinct blackish-gray infection point at the rachis or base of the spike. Spike drying can be partial or complete, depending on the infection site. Multiple infection points on a single rachis may occur under high inoculum pressure in susceptible genotypes. Infections at the rachis or peduncle disrupt the plant's nutrient transport system, causing all spikelets above the infection point to wither and die (Cruz and Valent, 2017). Gray, dark-gray, or black sporulation of the fungus is frequently visible at the infection sites in highly susceptible cultivars. In addition, infected awns may show brown to white discoloration, while glumes often exhibit elongated lesions with reddish-brown to dark-gray margins and a white to light-brown center (Islam et al., 2016). During the sporulation phase, lesions initially display gray centers that turn white to tan following spore release (Igarashi et al., 1986; Igarashi, 1990).

Figure 1. Blast and blast-like symptoms on wheat heads (Reference: Singh et al., 2021b). A-Wheat Blast (Gray Colored infection point), B- Fusarium Head Blight (Pink colored infection points), C- Spot Blotch (Black discoloration on the spikelet).

Under field conditions, the manifestation of leaf lesions varies substantially in configuration and size depending on the developmental stage of the crop. In susceptible cultivars, infection can occur as early as the seedling stage, often resulting in complete plant mortality under conducive environmental conditions (Igarashi, 1991; Singh, 2017). Even cultivars classified as resistant may exhibit moderately susceptible to susceptible reactions at the seedling stage when exposed to high disease pressure (Roy et al., 2022). The initial visual symptom on seedlings typically appears as a water-soaked, diamond-shaped lesion, which gradually develops a grayish-white center bordered by a dark brown margin as the disease progresses. As multiple lesions coalesce, extensive tissue necrosis ensues, ultimately leading to complete dehydration and death of the affected leaf (Islam et al., 2016).

Older leaves are more susceptible to infection by Magnaporthe oryzae pathotype Triticum (MoT) compared to younger foliage, particularly under favorable environmental conditions in susceptible cultivars (Cruz et al., 2015). On mature leaves, symptoms typically present as elliptical, elongated, or eye-shaped necrotic lesions, characterized by grayish to tan centers with distinct dark margins (Malaker et al., 2016). Although less frequently observed, lesions may also appear on the leaf collar, culm, culm nodes, and stem. Stem lesions are usually elongated or elliptical, exhibiting a bleached or whitish central area surrounded by dark brown to blackish borders (Islam et al., 2016).

Wheat blast exhibit symptoms that closely resemble those of Fusarium Head Blight (FHB) and spot blotch, which may lead to diagnostic errors in the absence of careful examination (Singh, 2017). Both wheat blast and FHB cause premature bleaching of spikelets; however, a key distinguishing feature lies in the characteristics of fungal sporulation. In FHB, infected spikelets often display abundant orange-pink spore masses, whereas wheat blast caused by *Magnaporthe oryzae* pathotype *Triticum* (MoT) produces gray sporulation on affected tissues (Wise and Woloshuk, 2010; Valent et al., 2016). In contrast, spot blotch, caused by *Bipolaris sorokiniana*, manifests as dark brown to black discoloration of spikelets. Typically, the infection is localized, with adjacent spikelets above and below the infection site often remaining healthy. Diagnostic challenges are further compounded when mixed infections occur, particularly between wheat blast and spot blotch, where symptomatology may overlap extensively, rendering visual differentiation unreliable without molecular or microscopic confirmation (Singh et al., 2021b).

Epidemiology of wheat blast

Wheat blast flourishes under specific climatic conditions, particularly warm temperatures (25–30°C), and high moisture, and recurrent precipitation— conditions frequently found in tropical and subtropical regions. The occurrence and progression of wheat blast are closely linked to specific climatic conditions, particularly the interaction between elevated temperatures and sustained spike wetness. Outbreaks are frequently associated with abnormal wet growing seasons, often triggered by El Niño Southern Oscillation (ENSO) events (Inoue et al., 2017). During the critical reproductive stage—especially anthesis—moderate temperatures (18–20 °C) combined with prolonged rainfall create highly conducive conditions for initial infection by the *Magnaporthe oryzae* Triticum pathotype (MoT) (Cruz and Valent, 2017). A subsequent rise in temperature, humidity, and solar radiation further enhances pathogen sporulation and accelerates disease spread (Islam et al., 2016). These environmental drivers not only facilitate epidemic development but also complicate timely management, particularly in susceptible cultivars (Kohli et al., 2011).

Cardoso et al. (2008) conducted investigation under controlled situation and observed that disease severity peaked at 30°C, with the intensity of infection increasing proportionally with longer intervals of spike wetness. Epidemics frequently coincide with such favorable conditions during wheat heading and grain filling stages. In contrast, the lowest disease expression was recorded at 25°C when spike wetness was limited to 10 hours. Notably, wetness periods shorter than 10 hours, irrespective of temperature, were not enough to trigger infection. However, under a system of 25°C with 40 constant hours of spike wetness, disease severity intensified beyond 85%. These findings are significant given that similar thermo-hygrometric conditions prevail in numerous wheat-producing regions worldwide. The disease is polycyclic, meaning it can produce multiple infection cycles in a single season, which prominently boosts its epidemic potential.

Building upon these observations, Cardoso et al. (2008) developed a predictive model delineating the relationship between blast intensity, ambient temperature, and spike wetness duration, offering a valuable tool for risk forecasting and management. Concurrently, Urashima et al. (2007) investigated the potential for aerial dispersion of the pathogen, employing molecular markers to exhibit that clonal populations of the fungus are capable of dispersing up to 1000 meters from their point of origin under favorable atmospheric conditions.

Infection process and disease cycle

The primary inoculum consists of conidia produced on crop residues, infected seeds, or nearby alternative hosts such as *Eleusine indica* (goose grass). These spores are spread by wind and rain splash, facilitating rapid and wide dissemination. Secondary infections often result in widespread crop damage within a few days, especially during the heading stage, which is the most vulnerable phase of wheat growth.

The disease cycle begins with the deposition of conidia on wheat spikes or leaves. Conidia germinate under favourable environment, producing germ tubes and then appressoria, specialized melanized infection structures that generate high turgor pressure to penetrate the cuticle and epidermis via mechanical force. Following penetration, biotrophic colonization initiates, with intracellular hyphae invading host cells without causing immediate cell death. This is succeeded by a necrotrophic phase, where extensive cellular lysis and tissue necrosis occur, leading to characteristic symptoms such as bleached spikelets and chlorotic lesions.

Under favourable situation these extremely conceptive hermaphroditic strains function as both male and female gametangia during crosses with strains of the opposite mating type. In addition, sexually competent *M. oryzae* strains give rise to a Phialophora-like anamorphic state, characterized by the formation of phialides that create characteristic, crescent-shaped microconidia (Chuma et al., 2009). Although these microconidia exhibit limited germinative capacity and penetrate host tissue through wound sites, their ecological function within the fungal life cycle remains ambiguous (Zhang etal., 2014). Both conidia and ascospore germinate on wheat tissue under moist and warm conditions, producing an appressorium that penetrates the host. Enter through stomata or direct penetration via appressoria. The fungus spreads intracellularly, moving cell-to-cell using biotrophic and later necrotrophic phases. In interactions with non-host or incompatible plant genotypes, fungal isolates often exhibit penetration failure; and successful entry may trigger cytoplasmic granulation or hypersensitive response (HR), indicative of effector-triggered immunity (ETI) consistent with a gene-for-gene resistance interaction (Araujo et al., 2016). Disease initially appear as gray-green lesions on spikes, turning into bleached spikelets, often without grain formation. Leaf symptoms may be present but are less common.

The pathogen that incites wheat blast is haploid, heterothallic ascomycete (Couch and Kohn, 2002). Sexual reproduction occurs via the fusion of compatible mating types, involving transfer of nuclei from spermatia to receptive ascogonia (Kang et al., 1994; Moreira et al., 2015). Pathogenic isolates are subdivided into distinct pathotypes based on host specificity, mating type, and genetic structure (Urashima et al., 1993; Tosa et al., 2004), with the *Triticum* pathotype (MoT) being uniquely adapted to infect *Triticum aestivum* and related species such as triticale and barley (Roy et al., 2020b, 2021a).

MoT survives between cropping seasons as conidia and mycelium on crop residues or infected seeds (Singh et al., 2021). Asexual reproduction is characterized by the production of pyriform, hyaline to pale grey, two-septate conidia borne sympodially on septate, light brown conidiophores. Infection involves appressorium-mediated penetration of the cuticle, followed by invasive hyphal colonization of host tissues (Tufan et al., 2009). The pathogen secretes phytotoxins and mycotoxins that facilitate biotrophic colonization (Patkar et al., 2015; Yan and Talbot, 2016). Although microconidia are formed in sexually fertile strains, their role in natural infection remains unclear (Zhang et al., 2014).

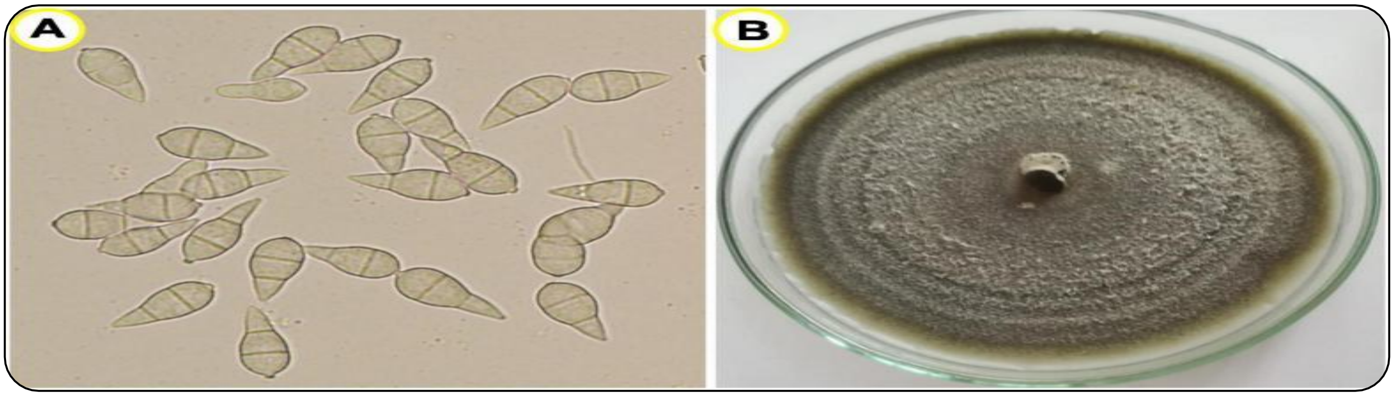

Figure 2. (A) Pyriform two-septate hyaline to pale, gray-colored asexual conidia (B) Dark gray-colored colony of the fungus grown on PDA medium. (Reference Singh et al., 2021b).

Wheat blast beyond borders: the globalization of a regional plant pathogen

Wheat blast was first documented in the Paraná state of Brazil in 1985 (Igarashi et al., 1986). Phylogenomic analyses suggest that the pathogen likely emerged via a host jump from indigenous *Poaceae* species to wheat (Castroagudín et al., 2017; Inoue et al., 2017), highlighting its ecological plasticity. The disease rapidly expanded across Brazil: reaching São Paulo and Mato Grosso do Sul by 1986, Rio Grande do Sul in 1987, Minas Gerais in 1990, Goiás in 1992, and the Federal District (Brasília) in 1993 (Igarashi, 1991; Prabhu et al., 1992; Anjos et al., 1996).

Establishment in South America

The warm and humid environment of the Brazilian Cerrado, particularly during wheat anthesis, provided an ideal microclimate for MoT proliferation. By the late 1990s and early 2000s, the disease had become endemic across major wheat-producing zones in eastern Bolivia (1996), eastern Paraguay (2002), and northern Argentina (2007). In affected areas, wheat blast has constrained cultivar deployment and disrupted cropping calendars, often requiring wheat farmers to abandon cultivation altogether.

Transboundary spread beyond South America

The first non-South American report of wheat blast occurred in 2011 in the United States, where a single infected wheat plant was identified in Princeton, Kentucky. Molecular studies later determined that the causal organism originated from a *Lolium*-infecting lineage endemic to the region, rather than a South American MoT strain (Farman et al., 2017).

A major incursion occurred in 2016 in Bangladesh, marking the first confirmed MoT outbreak in Asia. The disease affected ~15,000 ha across eight districts. Whole-genome analyses confirmed the Bangladesh isolate's South American lineage, indicating the likely introduction through MoT-contaminated wheat grain imports from Brazil (Callaway, 2016). The outbreak necessitated the incineration of infected fields and led to immediate wheat planting bans in affected areas.

In 2018, wheat blast was detected in Zambia, particularly within the Mpika district of Muchinga Province, under rainfed conditions (Tembo et al., 2020). The outbreak was observed in both farmer fields and research trials, and while its origin remains speculative, contaminated seed is strongly implicated.

Hot spots and regions where wheat blast prevails

Wheat blast has emerged as a significant threat in multiple wheat-growing regions worldwide, each characterized by environmental conditions conducive to the disease. In South America, the disease is well established in Brazil, Bolivia, Paraguay, and Argentina, where warm and humid climates with high rainfall during the heading stage of wheat create ideal conditions for pathogen development and spread (Cruz & Valent, 2017).

In South Asia, Bangladesh has confirmed outbreaks of wheat blast, while India maintains strict border surveillance due to its proximity and agro-climatic vulnerability. The high temperatures and relative humidity during the flowering stage in this region are particularly favorable for disease development (Islam et al., 2016). In Sub-Saharan Africa, Zambia has recently reported the presence of wheat blast. The country's agro-ecological conditions—characterized by warm, humid climates and substantial wheat cultivation—resemble those of affected areas in South America, suggesting a high potential for disease establishment and spread (Tembo et al., 2022).

Current management strategies

Managing this disease is complex due to its explosive spread, inadequate genetic resistance, adaptability to promising environments, and its seed-borne and airborne nature. An integrated disease management (IDM) approach is indispensable, combining host resistance, agronomic practices, chemical control, and biosecurity measures, supported by modern molecular and digital tools.

1. Breeding for resistance

Breeding for genetic resistance remains a cornerstone of wheat blast management, providing a sustainable and cost-effective solution (Bishnoi et al., 2022). Resistance breeding is challenged by the high variability and adaptability of MoT (Cruz et al., 2016; He et al., 2020). Resistance genes such as *Rmg2*, *Rmg3*, and *Rmg8* offer partial resistance but none provide complete protection under high disease pressure (Islam et al., 2019). Marker-assisted selection (MAS) and genomic selection are increasingly used to accelerate the development of resistant lines (Song et al., 2023).

a. Genetic sources of resistance

Resistance breeding has significantly developed through the investigation of dissimilar genetic sources, including synthetic hexaploid wheat, wild relatives, and selected cultivars from South America and South Asia. Among the most prominent introgressions is the 2NS/2AS translocation from *Aegilops ventricosa*, which has been extensively assimilated into elite wheat lines for its partial resistance to several pathogens (Juliana et al., 2019). While this translocation offers an appreciated layer of resistance, its usefulness can be compromised under high disease pressure or in the presence of highly virulent or diverse pathogen races (Gao *et al*., 2021; Hossain, 2022). These limitations emphasize the prerequisite for persistent germplasm screening and highlight the significance of wild relatives as pools of novel resistance genes. Incorporating such diverse sources remains a foundation of modern breeding strategies aimed at accomplishing durable and broad-spectrum resistance (Kaur et al., 2018).

b. Molecular tools and genomic selection

Recent improvements in molecular breeding, particularly marker-assisted selection (MAS) and genomic selection (GS), have hastened the development of disease-resistant wheat varieties significantly. The identification of key quantitative trait loci (QTLs) associated with resistance—such as those located on chromosomes 2NS, 3BS, and 5BL—has simplified targeted breeding strategies (Singh et al., 2021). Furthermore, the integration of high-throughput phenotyping platforms has enhanced the precision and efficiency of selection within segregating populations. These technologies are enabling breeders to dissect complex resistance traits more effectively and to pyramid multiple resistance genes, thereby contributing to the improvement of cultivars with broad-spectrum and durable resistance.

c. Pre-breeding and collaborative platforms

Collaborative initiatives involving international research centers such as the International Maize and Wheat Improvement Center (CIMMYT) and the International Center for Agricultural Research in the Dry Areas (ICARDA) play a central role in the global effort to combat wheat diseases. These centers facilitate the exchange of germplasm, conduct pre-breeding activities, and lead multilocation testing under diverse agro-ecological conditions. Such coordinated efforts are critical for identifying and deploying sources of durable resistance that remain effective across environments and against evolving pathogen populations (Mottaleb et al., 2018).

2. Agronomic practices used for management of wheat blast

Given that wheat blast development is strongly influenced by agro-ecological conditions, strategic crop management decisions such as planting date, crop rotation, and field sanitation can substantially impact disease incidence and severity (Cruz & Valent, 2017; Kohli et al., 2011). Incorporating these practices into broader disease management frameworks enhances the effectiveness of resistance genes and fungicides, particularly in high-risk environments.

a. Adjustment of sowing time

Agronomic practices are a vital component of the integrated management of wheat blast (WB), complementing both genetic resistance and chemical control measures. One of the most effective cultural interventions is the manipulation of sowing dates to avoid heading during periods of high humidity and temperature conditions that favor MoT infection. Early or late sowing can reduce spike exposure to favorable conditions for disease development (Islam et al., 2020).

b. Crop rotation and field sanitation

The risk of wheat blast is markedly elevated under continuous wheat cultivation, particularly in regions with high inoculum pressure. Rotating wheat with non-host crops such as legumes or oilseeds serves as an effective strategy to break the disease cycle by limiting the survival and propagation of the pathogen (Pagani et al., 2014). Furthermore, proper residue management—including the removal or deep incorporation of infected plant debris can significantly reduce the availability of primary inoculum. Practices such as deep plowing help to bury infected residues, thereby minimizing the surface-level dispersal of conidia and contributing to a reduction in overall disease incidence.

c. Balanced fertilization and irrigation management

Effective nutrient and water management are critical components of an integrated strategy for managing wheat blast, particularly in environments conducive to disease development. Unnecessary nitrogen fertilization has been shown to intensify wheat blast vulnerability by encouraging excessive vegetative growth and the establishment of a dense canopy, which extends leaf moisture interval and generates a promising microenvironment for *Magnaporthe oryzae* pathotype *Triticum* (MoT) infection. This luxurious canopy can retain moisture for prolonged phases, especially during critical growth stages such as heading, thereby increasing the likelihood of pathogen colonization and spike infection (Maciel, 2011).

To frustrate these effects, a balanced nutrient management regime is recommended. Sufficient levels of potassium and key micronutrients such as zinc and boron are known to enrich plant defense mechanisms, reinforce cell walls, and decrease disease severity. Potassium, in particular, plays an essential role in improving stress tolerance and decreasing disease incidence by improving water regulation and enzyme activity within the plant.

Water management is critical equally in disease suppression. Overhead irrigation during sensitive phases of wheat development—particularly heading and flowering should be circumvented, as it upsurges spike dampness and enables spore germination and infection. As an alternative, the usage of drip or furrow irrigation systems, planned to avoid critical infection windows, can help alleviate disease pressure. In regions where irrigation scheduling is likely, improving watering times to curtail canopy humidity during evening and night hours can more decrease the danger of wheat blast outbreaks.

When executed in combination with host resistance and fungicide application, integrated nutrient and water management practices not only contribute to suppress disease but also endorse overall crop health and yield under disease-prone conditions

d. Use of certified disease-free seed

Seedborne transmission of *Magnaporthe oryzae* pathotype *Triticum* (MoT) presents a serious hazard to wheat production, particularly in areas where the pathogen is not yet prevalent. MoT-infected seed can serve as a dormant source of primary inoculum, enabling local disease occurrences and facilitating transboundary distribution of wheat blast through trade and informal seed exchange networks. Hence, ensuring the usage of pathogen-free seed is a preliminary element in any wheat blast prevention and management strategy.

The use of MoT-free (Magnaporthe oryzae pathotype Triticum) seed lots verified through highly sensitive and specific molecular diagnostic assays is essential for preventing the introduction and establishment of wheat blast in new regions. Advanced molecular techniques, such as conventional PCR and real-time quantitative PCR (qPCR), have been developed for the reliable detection of MoT in seed samples with high sensitivity and specificity. These tools enable the early and accurate identification of the pathogen, even in asymptomatic seeds, thereby strengthening the integrity and reliability of seed health certification programs.

Certified seed systems are fundamental to maintaining and disseminating pathogen-free planting material. To ensure their efficacy, these systems must adhere to stringent seed health standards, which encompass routine laboratory diagnostics, systematic field inspections, and post-harvest seed treatment protocols. Additionally, the implementation of phytosanitary measures in compliance with international frameworks such as those established by the Food and Agriculture Organization (FAO) and the International Plant Protection Convention (IPPC) is critical for mitigating the risk of *Magnaporthe oryzae* pathotype *Triticum* (MoT) spread through seed trade and movement (FAO/IPPC, 2018).

In regions endemic for wheat blast, continuous monitoring of seed lots and rigorous surveillance at entry points for imported seed are critical components of an effective plant health management system. The enforcement of quarantine regulations, stringent import restrictions on uncertified seed, and awareness programs targeting seed producers and farmers further reduce the risk of pathogen introduction, establishment, and subsequent epidemic outbreaks.

In summary, the combination of seed health diagnostics, certified seed systems, and phytosanitary protocols forms a comprehensive strategy for managing the seed borne threat of wheat blast and protecting global wheat production systems from this emerging pathogen.

e. Avoiding wheat cultivation adjacent to infected fields

Maintaining spatial separation between wheat fields and potential sources of inoculum, such as infected rice or volunteer wheat, can limit pathogen spread. Buffer zones, fallow strips, or rotation with non-host crops can act as physical barriers to conidial dissemination.

The "wheat holiday" strategy involves the temporary suspension of wheat cultivation in wheat blast affected or high-risk areas to halt the spread of *Magnaporthe oryzae* pathotype *Triticum* (MoT). Its success depends on both enforcement and the provision of viable alternative crops, especially for resource-poor farmers. India has banned wheat cultivation within 5 km of the Bangladesh border, promoting legumes and oilseeds, while West Bengal has enforced a three-year ban in key districts (ICAR-IIWBR, 2020). In Bangladesh, crops like maize, onion, garlic, and lentil have shown promise as profitable substitutes (Mottaleb et al., 2019). However, alternative crops must not act as MoT hosts, and the management of weedy reservoirs remains a critical challenge for the strategy’s long-term success.

f. Intercropping and landscape management

Although less widely studied, intercropping systems or the use of windbreaks may reduce disease pressure by altering microclimatic conditions or impeding long-distance conidial transport. This approach warrants further investigation in diverse agro-ecosystems (Mottaleb et al., 2018).

Collectively, these agronomic interventions serve as environmentally sound**,** cost-effective, and locally adaptable strategies that should be promoted within an Integrated Disease Management (IDM) framework. Their success depends on region-specific risk assessments, farmer education, and integration with resistant cultivars and fungicide use.

3. Epidemiological forecasting tools

Epidemiological modeling and forecasting tools are indispensable components of modern disease management, allowing stakeholders to anticipate outbreaks, optimize interventions, and reduce unnecessary fungicide use (Maciel, 2011).

a. Climatic risk mapping

Predictive models based on temperature, humidity, and rainfall patterns have been developed to identify blast-conducive zones. For instance, tools such as the Blast Risk Index (BRI) are used to evaluate daily or weekly risk of WB in real-time, based on weather parameters critical to MoT infection cycles (Fernandes et al., 2017).

b. Spatial modeling and surveillance integration

Geospatial and temporal models integrating surveillance data, cropping systems, and climate variability have improved early warning systems. These models can simulate aerosolized conidia spread, particularly during heading stages, enabling timely alerts and targeted fungicide applications (Pieck et al., 2017).

c. Decision support systems (DSS)

Development of decision support systems linked with digital platforms and mobile advisory services holds great promise for resource-poor farmers in endemic areas. These tools assist in making informed decisions on sowing dates, cultivar choice, and disease management strategies in near real-time (Mottaleb et al., 2018).

4. Application of fungicides in wheat blast management

Fungicide application is a key strategy in the integrated management of wheat blast, particularly in regions where the disease has become endemic. The primary chemical classes used are demethylation inhibitors (DMIs; e.g., triazoles) and quinone outside inhibitors (QoIs; e.g., strobilurins)**,** which target critical stages in the disease cycle of *Magnaporthe oryzae* pathotype *Triticum* (MoT), especially during heading and early grain development (Cruz et al., 2015; Goulart & Souza, 2001).

Among DMIs, tebuconazole and propiconazole have shown moderate to high efficacy when applied preventatively or at early infection stages. Likewise, QoIs such as azoxystrobin are commonly used in field settings, although their performance is often inconsistent under high disease pressure or in regions with fungicide-resistant isolates (Castroagudín et al., 2015; Pagani et al., 2014). The development of fungicide resistance in MoT populations has been documented in South America (Fernandes et al., 2017; Dorigan et al., 2019), emphasizing the urgent need for fungicide stewardship. Sustainable disease management necessitates the judicious use of fungicides, integrated with effective field management practices and adherence to appropriate reapplication intervals—particularly avoiding consecutive applications of fungicides from the same mode-of-action group. These strategies are critical to preserving fungicide efficacy and mitigating the risk of resistance development (Corkley et al., 2021).

Advancements in disease forecasting tools and epidemiological modeling have further improved fungicide use efficiency by identifying high-risk infection windows, thereby allowing site-specific and time-optimized applications (Cruz & Valent, 2017). These tools, when integrated with weather-based models and remote sensing technologies, contribute to sustainable blast management by minimizing unnecessary chemical inputs and mitigating environmental risks.

Although fungicides play a critical role, they are insufficient on their own to control wheat blast during epidemic outbreaks. Therefore, their use should be integrated within a comprehensive Integrated Disease Management (IDM) strategy, incorporating the deployment of blast-resistant cultivars, crop rotation, residue management, and stringent quarantine measures to reduce inoculum pressure and mitigate the risk of disease resurgence (Islam et al., 2020).

5. Quarantine measures against wheat blast

Quarantine protocols are a fundamental of plant biosecurity and serve as the first line of defense against the introduction and dispersed of wheat blast (WB). Given the transboundary nature of this disease and its capacity for rapid dissemination via infected seed and airborne conidia, phytosanitary measures are essential for containment, especially in regions currently free from the pathogen Restricting movement of infected seed and plant material; enforcing phytosanitary regulations (CIMMYT, 2016; Islam et al., 2020).

International and national quarantine strategies focus on three key areas

Seed Health Regulations – Since MoT is seed-borne, strict seed certification schemes and import restrictions are imposed on wheat seed originating from blast-endemic country, particularly South America and parts of South Asia (FAO/IPPC, 2018). Only pathogen-free seed verified through diagnostic testing (e.g., PCR-based assays) is permitted for international movement.

Surveillance and Early Detection – Effective quarantine requires robust surveillance systems at ports of entry and in border regions. These systems are increasingly supported by molecular diagnostics, geo-referenced mapping, and the deployment of sentinel plots for early warning and rapid response (Cruz & Valent, 2017).

Containment and Eradication Protocols – In the event of incursion, regulatory authorities implement emergency response plans that include movement restrictions, destruction of infected plant material, decontamination procedures, and temporary bans on wheat cultivation in affected zones (Kohli et al., 2011). Collaboration with regional plant protection organizations is vital to coordinate cross-border efforts.

Recent outbreaks, such as the 2016 emergence of wheat blast in Bangladesh, have demonstrated the inadequacy of conventional quarantine alone and highlighted the need for regional cooperation, rapid information exchange, and capacity building in diagnostic capabilities and risk assessment frameworks (Islam et al., 2020).

Therefore, quarantine must be viewed not as an isolated measure, but as an integrated component of a broader biosecurity framework**,** which includes resistant germplasm deployment, cultural practices, and fungicide application to limit pathogen establishment and spread.

Wheat blast in South Asia: A looming crisis for regional food security

The dietary pattern in South Asia is dominated by cereals of which wheat is an important constituent (Kataki et al. 2001). The green revolution in South Asia (Farmer, 1981) has made the region self-sufficient in wheat, with the region producing approximately 20% of total wheat produced and 25% of total area under wheat cultivation in the world by 2020. The emergence of wheat blast, represents a formidable threat to sustainable wheat production. Initially confined to South America, wheat blast has transcended geographical barriers, establishing its self in new agro-ecological regions and triggering significant economic and food security concerns.

P. oryzae is a hemibiotrophic pathogen with a broad host range within the Poaceae family. The pathotype infecting wheat (MoT) exhibits a high degree of aggressiveness, particularly during anthesis, when humidity and temperature synergize to favor conidial germination and appressorial penetration. The pathogen's capacity for aerial dispersal, coupled with globalized grain trade, enhances its transcontinental migration potential. Its resilience under favorable conditions makes it exceptionally difficult to eradicate once introduced.

South Asia remained free of wheat blast until February 2016, when an unexpected outbreak occurred in Bangladesh. Approximately 15,000 hectares across eight districts suffered complete or near-total yield losses, attributed to unseasonal rainfall events and the inadvertent introduction of MoT, most likely via infected seed or other contaminated plant material. Molecular and phylogenetic analyses confirmed the South American origin of the Bangladeshi isolates (Islam et al., 2016), illustrating the pathogen's capacity for long-distance intercontinental dissemination. The incursion of wheat blast into South Asia—especially Bangladesh—has raised alarms about its potential spread into the Indo-Gangetic Plains, one of the world's most critical wheat-producing regions. This is especially concerning given the region's reliance on wheat as a staple food crop (Islam and Gupta, 2025).

The rapid spread and severity of the disease led to the adoption of drastic containment measures, including field burning, to suppress inoculum load and prevent secondary infection cycles. This incursion marked a pivotal shift in regional plant pathology priorities, with wheat blast emerging as a central focus of disease surveillance and breeding efforts.

Climatic modeling studies (Mottaleb et al., 2018; Islam et al., 2019) estimate that over 60% of South Asia's wheat-growing areas possess the agro-ecological prerequisites conducive to wheat blast establishment, including:

- High relative humidity during flowering,
- Mild to warm temperatures (18–30°C),
- Dense cropping systems, particularly wheat-rice rotations,
- Presence of susceptible wheat genotypes and alternative Poaceae hosts.

Such conditions prevail in several southeastern and southern agro-ecological zones of Pakistan, underscoring the urgent need for pest risk analysis (PRA) and preemptive containment strategies.

The introduction of wheat blast into the subcontinent poses grave agronomic and socio-economic consequences. South Asia consumes approximately 100 million tonnes of wheat annually, and over 300 million people depend on it as a primary caloric source. The pathogen's incursion threatens not only yield stability but also seed quality, market supply chains, and national food reserves, aggravating food insecurity under climate change scenarios.

From an agronomic perspective, wheat blast challenges traditional cropping calendars and cultivar deployment strategies. The lack of durable host resistance, coupled with fungicide inefficacy under field conditions, limits current management options. CIMMYT (2019) reports that conventional triazole- and strobilurin-based fungicides offer only partial disease suppression, particularly when infection coincides with flowering.

Effective wheat blast management requires a multi-pronged Integrated Disease Management (IDM) approach comprising:

- Development and deployment of resistant cultivars through marker-assisted selection and introgression from known resistant sources (e.g., *2NS translocation lines*),
- Adjustments in sowing dates to avoid peak infection windows,
- Seed health certification and quarantine enforcement to restrict cross-border pathogen movement,
- Improved surveillance systems, including remote sensing and molecular diagnostics, for early detection and spatial tracking.

Furthermore, international collaboration and sustained financial and institutional support are crucial to strengthen regional phytosanitary capacity and facilitate knowledge transfer between South America and South Asia.

The 2016 wheat blast outbreak in Bangladesh serves as a sentinel event, emphasizing the pathogen's adaptability and the vulnerabilities of modern agricultural systems. As Pakistan and other neighboring countries remain at risk, it is imperative to prioritize wheat blast within national disease preparedness frameworks. Proactive interventions—anchored in sound agronomic principles and plant pathological insights—are essential to mitigate the threat and preserve wheat as a pillar of food security in the region

CONCLUSION

This review article critically examines the present scenario of wheat blast (WB) in affected regions cosmopolitan and evaluates the disease management strategies adopted to control its relative incidence beneath economical damaging thresholds. Emphasis is placed on the crucial role of epidemiological research work conducted in knowing disease dynamics and revealing effective management decisions. Recent progression in the improvement of predictive modeling tools for prediction WB outbreaks is also discussed. Moreover, the article furnish an summary of current investigation attempts aimed at explicate integrated disease management (IDM) strategies. These include phytosanitary (quarantine) measures, optimized agronomic practices, deployment of genetically resistant cultivars, and strategic fungicide interventions, all of which are essential elements in diminishing the hazard of future epidemics. Combining host resistance with climate-informed decision-making tools represents a proactive and adaptive approach to WB mitigation. Future efforts should focus on pyramiding multiple resistance genes and enhancing model precision through machine learning and remote sensing. Given the aggressive nature of wheat blast and its potential to compromise food security, it is imperative for the global scientific community to prioritize research on this issue. Enhanced surveillance, development of resistant wheat varieties, and international collaboration are crucial steps toward mitigating the threat posed by wheat blast.

AUTHOR CONTRIBUTIONS

This project was conceptualized by Nadeem Ahmad and Amir Afzal, and its successful execution was the end result of the dedicated hard work of the entire team. Recognizing individual contributions alone would not do justice to the really combined spirit in which this effort was undertaken

COMPETING OF INTEREST

The authors declare no competing interests.

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