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Current Status of Rice Blast in Vietnam and Future Perspectives

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Abstract

The rice blast disease caused by the fungus *Pyricularia oryzae* has become one of the greatest concerns of rice farmers in Vietnam. This review discusses the current status of rice blast as well as its social and economic impacts. This review also further examines the current management strategies used to combat blast disease, and evaluate their efficacy. Among several commonly used strategies, this review will also discuss emerging and largely underexplored strategies including biocontrol methods. Finally, this review will provide a comprehensive summary on the current state of the disease and propose plans of action to mitigate these challenges in the context of Vietnam's agriculture.

Subject Areas

Agricultural Science

Keywords

Agriculture, Biocontrol, Crop Cultivation, Fungicides, Rice Blast Fungus, Management Strategies

1. Introduction

Rice (*Oryza sativa*) is one of the most widely consumed grains globally. It is a domesticated cereal crop in the Poaceae family and is cultivated by 113 countries in the world, producing more than 700 million tons per year [1]. Southeast Asia accounts for about 30 percent of total harvests and 48 million ha in the region are dedicated to cultivation [2]. In light of a growing global population set to reach 9.6 billion by 2050, rice supplies are unlikely to meet projected demands because of many challenges such as climate change and declining availability of land and water resources [3].

In addition, one of the most major biotic stresses on rice production is rice blast disease caused by *Pyricularia oryzae*, increasing the vulnerability of food systems in the region [4]. The emergence and re-emergence of this fungal pathogen are a result of excessive applications of nitrogen fertilizers, scarcity of water resources, lack of proper drainage systems, as well as climate change. According to reports by the Rockefeller Foundation in 1991, infected areas in the region suffer combined losses of 8.8 kg/ha and approximately 40.9 million USD annually [5]. Most notably, in Vietnam, where 40 percent of total land area is used for cultivation and approximately 40 million inhabitants work in agricultural industries, blast disease stands as a major threat to food security and exports that bring in foreign currency [6]. Moreover, the country's humid and tropical climate provides favorable conditions for the emergence and spread of fungal pathogens such as blast fungus. Some approaches to manage blast that farmers frequently opt for include fungicides and resistant varieties, which are both easily accessible and affordable. However, due to the pathogen's evolutionary potential and durable resistance, both these methods are largely ineffective and the fungus quickly develops a tolerance [7].

This review will describe the current management practices used to control rice blast and describe under-explored solutions. Based on these descriptions, this paper will consider future directions for research expansion as well as the potential of precise programs for effective detection, monitor, forecast, and management of this disease in Vietnam in consideration of the benefits and drawbacks of each described strategy.

2. Pathogen Biology of *P. oryzae*

P. oryzae (syn. *Magnporthe oryzae*) is a heterothallic ascomycete than can reproduce by both asexual and sexual manners [8]. The conidia of the fungus size are 25 - 30 × 8 - 10 μm and are translucent with two septations. They are also pyriform and have an acute apex [9]. While there are cross-infectivity and host shifts between *P. oryzae* and *P. grisea*, it should be noted that *P. oryzae* is pathogenic on rice while *P. grisea* is a pathogen of crabgrass. For the purpose of this review, *P. oryzae* will be mainly discussed.

The fungus affects the aerial parts of the plants at any growth stage and produces symptoms such as leaf blast, node blast, collar rot, neck rot, and panicle blast [10]. For instance, leaf blast can display white to gray-green lesions that are elongated diamond shape or eye shaped with pointed ends [11]. Collar infections may show brown "collar rot" symptoms and stem nodes are usually affected as the plant reaches maturity [12]. While studies have identified the ability of the fungus to infect the root before spreading to the aerial parts of the plant, the exact nature of this process is not fully understood [13].

In addition, transmission rates of the disease are influenced by a variety of factors, such as temperature conditions, moisture levels, relative humidity, and soil types [14]. Long periods of leaf wetness also correlate with higher infection frequencies [15]. Differences were observed between rice plants in lowland and upland conditions, where the former favors blast development [16]. Temperatures of 17˚C to 28˚C and high relative humidity of 95% resulted in more spores being released [17]. Under elevated CO_2 concentrations and low solar radiation, blast susceptibility of rice plants also increases [18].

3. Management Strategies and Techniques

3.1. Cultural Practices

Certain traditional cultural practices have also been utilized to manage rice blast. As part of a Rice Industry Biosecurity Plan by Plant Health Australia in 2009, it is suggested that affected grains should be segregated to prevent spreading to other rice-growing areas [19]. In addition, broadcasting methods—which involve the random scattering of seeds over soil surfaces—are strongly cautioned against as they create uneven plant distributions due to seed clusters, contributing to a more favorable microclimate for blast infections [20]. Studies have pinpointed that sowing dates also impact disease incidence and severity as they are subjected to weathering conditions—such as low temperature and high humidity—that can similarly produce favorable disease conditions [20]. Meanwhile, hand weeding can serve to remove alternate hosts for pathogens which can reduce soil and airborne diseases in crop environments [20]. Using split doses of nitrogen fertilizers also reduced blast severity compared to single applications of N on susceptible cultivars [21]. Applications of silicon (Si), besides forming physical barriers on leaf epidermis against invading pathogens, can also mediate certain defense responses in rice plants to increase their resistance, and thus are highly recommended [22]. Other traditional preventive measures against blast involve maintaining flood levels—from 2 - 8 inches—in rice fields until draining stage before harvest to create anaerobic conditions that can minimize disease development [23]. These cultural practices are particularly useful as they prevent the onset and development of blast in its initial stages.

Despite providing an economical and eco-friendly solution with minimal impacts on the environment, these cultural practices are time-consuming and labour-intensive, yielding low production efficiencies. In addition, because cultural practices are likely inspired by indigenous knowledge to maintain agricultural systems over many thousands of years of farmer's experience, these practices are likely undocumented and drastically differ amongst varying communities and cultures. Cultural and language differences coupled with the geographical separation of communities together prevent the widespread applications of these indigenous practices, and will require further scientific guidelines to translate and simplify these practices into one ubiquitous guide for everyone to use.

3.2. Resistant Varieties

Plant breeding efforts and genome editing techniques have been rigorously developed to advance the developments of rice cultivars against rice blast. To understand the fungal mechanisms of pathogenesis, studies have examined both avirulence (*AVR*) genes of *P. oryzae* and *R* genes of host plants under favorable conditions [24]. There have also been efforts to develop high-yielding rice cultivars carrying a single dominant *R* gene that corresponds to a single dominant *AVR* gene in pathogen strains [25]. Out of the 40 *AVR* genes that have been isolated from *P. oryzae* [26], 11 of them have been cloned and characterized, including *PWL2*, *AVR-Pita1*, AVR-Pib, *ACE1*, *AVR-Pizt*, *AVR-Pik*, *AVR-CO39*, *AVR-Pia* and *AVR-Pii*, *AVR-Pi9*, and *AVR-Pi54* [27]-[32]. Since *PWL2* and *AVR-Pita* encode putative secreted proteins, studies have suggested that protein secretion is essential to the function of *AVR* genes [29]. On the other hand, more than 25 *R* genes to races of *P. oryzae* have been characterized genetically [33].

For instance, the putative mature of *AVR-Pita1* is $AVR\text{-}Pita_{176}$, which interacts with rice *Pi-ta R* gene to trigger a *Pi-ta* mediated defense response expressed in cells [34]. However, other research has also shown that *AVR-Pita* in certain *P. oryzae* strains can demonstrate mutations, including point mutation, deletion, and insertion of transposons to overcome resistance of *Pi-ta* gene [31]. Another example is the *AVR-Pib* gene which interacts with *Pib R* gene by encoding a 75-residue protein that contains a signal peptide [32]. Similarly, the *Pik* gene is resistant to isolates of *P. oryzae* containing *AVR-Pik* gene [35].

Although resistance varieties have been adopted as one of the more effective and economical measures to control blast, there are a few major problems to their application. Firstly, the use of gene editing technologies raise many ethical questions, thereby leading to resistance in the general public to adopt these newly developed technologies [36]. In addition, the high variability of *P. oryzae* isolates allows for the frequent emergence of novel virulent races [37]. This makes the control of blast difficult as resistance is often lost after 3 - 5 years of cultivation, emphasizing the need to develop broad spectrum and durable resistance in rice [38].

Currently, in Vietnam, with the high variability of the fungal pathogen *P. oryzae*, pathogenicity tests and other molecular techniques have also been used to characterize the genotypic and phenotypic diversity of *P. oryzae*. However, since breeding for resistance requires a complex understanding of the distinct genetic groups of *P. oryzae*, the use of resistant cultivars in Vietnam has been greatly limited due to the lack of understanding on the pathogen population in the area. Most recently, a study by [39] identified an optimal set of AFLP primer combinations to genetically analyze *P. oryzae* populations, and determined more variable pathogenicity in populations in the Northern region near the Red River Delta compared to the Southern regions. However, more samples are still needed to accurately measure biological evolution of *P. oryzae* populations.

3.3. Chemical Fungicides

Due to their cost and accessibility, rice farmers heavily depend on chemical-based control methods to manage rice blast disease. Because these methods have such high efficacy, approximately 8.4% of the global fungicide market is dedicated to the rice industry [40]. Multiple factors that contribute to fungicide efficacy include inoculum levels, spray volume, type of adjuvants added, and weather conditions [40]. Specifically, rainfall may lower the fungicidal activity of the chemical disease in field trials [41]. In order to maximize returns for fungicide applications, other factors such as application timing and method are also of critical importance [42]. Currently, the large number of pesticides used are classified into two main categories: seed treatment and foliar spraying.

Seed treatments are applied to the seed surface prior to sowing and provide protection for rice plants from an early stage to prevent the interference of blast pathogens, especially during the seed germination process [43]. Major benefits to this treatment method include demonstrated high efficacy and minimal residues despite using low doses for application. In addition to seed treatments, foliar sprays are another method of applying pesticides to plants. Specifically, foliar sprays are applied directly onto plant foliage as sprays with contact or systemic effects at three different stages: tillering stage, bootleaf stage, and grain filling stage [44].

For instance, tricyclazole is one of the commonly used treatments. Studies have proposed that tricyclazole belong to the melanin biosynthesis inhibitors (MBI) group fungicide and inhibits polyhydroxynapthaline reductase which inhibits melanization within the appressorium and prevents penetration of the epidermis by the fungus [45]. Besides tricyclazole, other fungicides such as pyroquilon, phthalide, and carpropamid also target enzymes in the biosynthesis pathway of dihydroxynaphthalene (DHN) melanin [46]. On the other hand, Isoprothiolane targets the infecting hyphae of the fungus at its penetration and growth stages instead of during conidial germination and appressorium formation [47]. Several studies have also revealed that new combination fungicides have also demonstrated efficiency against the disease. Multiple fungicides also reduced disease incidence more when applied twice rather than once. The performance of fungicides in controlling rice blast disease caused by *P. oryzae* is shown in **Table 1**. Moreover, these fungicides should be used alternatively to prevent the development of resistance due to the repeated use of a single fungicide. It is also of note that fungicides can produce lower levels of activity against rice blast disease in field trials compared to laboratory tests [48]. Currently, Vietnamese farmers extensively use these pesticides to treat rice blast, including Tricyclazole, Carbendazim, and Azoxystrobin [49]. While Carbendazim is prohibited by the US Environmental Protection Agency, it is still widely applied in VIetnam due to its persistent nature with a half-life of 320 days [50].

However, certain limitations to this methodology include scenarios where materials are deposited in the upper third of the canopy when applied by air, and rain and dew are subsequently required to relocate fungicide into area of lower canopy with disease [55]. Thus, fungicidal activity is reduced due to weathering effects, and further impacted by other physical factors such as drift, calibration

Table 1. Summary of fungicidal activities of commonly-used fungicides against blast disease.

Fungicide(s)	Treatment Method	Results	Study
Carbendazim 50 WP	sprayed three times at weekly interval starting with disease initiation at doses of 1 g/L/kg	32.91% disease control	[51]
Tricyclazole 75% WP	applied five times at weekly interval with varying doses of 2 mL/L of H_2O	35.5% disease incidence and 27.85% disease severity	[52]
Tricyclazole 45% + hexaconazole 10 WG	applied separately after appearance of disease, followed by two sprays at 10 to 15 days interval	32.41% disease incidence and 14.34% disease intensity	[53]
Carbendazim 50% SC	applied twice with doses of 0.75 mL	9.04% disease incidence	[48]
Azoxystrobin + Difenoconazole	inoculation performed on conidial suspension of *P. grisea*, *i.e.* 2×10^7 conidia/ml at tillering and boot stage during evening hours	51.3% leaf blast severity and 39.0% neck blast incidence	[54]

errors, and volatility [55]. Timing of applications, specifically in relation to rainfall, can also result in reduced yield performance due to the loss of fungicides before plant absorption [55]. It should be highlighted that fungicide efficiencies have also been frequently compromised due to the occurrence of fungicide resistance with gene mutations and mechanisms induced upon fungicide stress in phytopathogens [56].

Although synthetic fungicides are effective choices for control against plant diseases, there is growing public concern from research regarding their toxicity and their subsequent effects on environment and human health. Irrational applications of fungicides can lead to serious environmental issues, including but not limited to soil quality reduction, residues in rice grains, and threats to biodiversity and aquatic ecosystems [57]. After applications in agricultural fields, fungicides are often carried into streams via runoff with detrimental effects to freshwater ecosystems [58]. In other scenarios, fungicide chemicals infiltrate groundwater sources, and for regions where side streams and groundwater are utilized for irrigation, crops are vulnerable to high concentrations of toxic chemicals [59] [60]. Furthermore, non-target organisms in nearby communities are also negatively impacted, including black flies and bees that have major physiological changes following exposure, as some studies have highlighted [25] [61]. Most relevant to rice consumers and farmers, various routes of exposure such as inhalation of spray mists or consumption of seed grains can result in acute and chronic poisoning in humans, posing major threats to human health [62].

3.4. Use of Botanicals

Plant extracts can also be utilized for treatment of blast disease for their medicinal and antimicrobial properties. Because expenses for chemical pesticides can be high, natural chemicals from plants provide a cost-effective and readily available option to farmers in developing countries [63]. These botanical extracts are also safe, biodegradable, and eco-friendly [64]. More specifically, studies have also shown that selected plant extracts are not phytotoxic to rice seedlings and plant development [65]. As seen in **Table 2**, multiple extracts have been tested for efficacy in both *in-vitro* and *in-vivo* conditions.

For instance, the leaves of *P. caninum* and *P. betle* var. contain a variety of bioactive compounds, including alkaloids, flavonoids, steroids, hydroxychavicol, and other phytochemicals which exhibit insecticidal and fungicidal properties that are particularly useful against plant diseases [68] [69]. Similarly, *E. aromatica* extracts also contain eugenol in the clove which exhibit antimicrobial properties that are potentially responsible for the antifungal activity observed on *P. oryzae* [67]. While the inhibitory effects of *Phyllostachys pubescens*, or bamboo leaf extracts, have been studied in a study in Hiroshima, Japan on the wild rice *Oryza rufipogon* grown in Southern Vietnam, there are no currently existing studies on the application of botanical extracts to treat blast disease that were conducted directly in Vietnam [33].

Thus, the antifungal potential of these medicinal plant extracts demonstrate potential for the management of blast disease. Combinations of multiple extracts can form new compounds to increase antifungal activity and should be considered. While the search for these bioactive compounds is much desired, this method can also be limited due to factors such as plant availability and the complexity of bioactive compound structures that are difficult to characterize and synthesize, while being liable to decomposition over time [70]. Application of plant extracts can also be labor-intensive and expensive for farmers. Similarly, further field trials under different cropping seasons and agro-climatic zones are recommended to identify locally available medicinal plants that are suitable as botanicals.

Table 2. Summary of previous experiments on bioefficacy of botanical extracts against blast disease.

Extract (s)	Treatment Method	Results	Study
Allium sativum	rice seeds pre-inoculated with *P. grisea* were soaked in suspensions of 25% concentration of extract overnight	68.75% inhibition of mycelial growth	[65]
Piper caninum + *Piper betle* var.	2% of composite extracts mixed with plant-growth promoting bacteria (PGPR) to spray on surface of rice seedlings and measurements taken after 8 weeks	86.87% inhibition of fungal growth and 9.19% reduction in disease intensity	[66]
Eugenia aromatica	1 mL of plant extract of 10% concentration applied using poisoned food technique	75% mycelial growth inhibition and 77% inhibition of sporulation	[67]

3.5. Biocontrol Agents

Microbial biocontrol agents can also be used to suppress rice blast. The criteria to determine their efficiency relies on the antagonistic activity against rice blast in both *in vitro* and *in vivo* experiments. While many biocontrol agents of rice blast have been studied, including *Pseudomonas fluorescens* and *Sphingomonas sp.* strains, *Streptomyces spp.* seem to be the most well-studied in both in-vitro and in-vivo conditions.

Streptomyces spp. belongs to the *Streptomyces* genus, which consists of a group of Gram-positive, aerobic, and non-acid fast bacteria with a shape that resembles filamentous fungi [71]. *Streptomyces* form a layer of hyphae that can differentiate into unigenomic prespore compartments through regulated cell division which eventually mature into thick-walled spores suitable for dispersal and survival [72]. The ability of *Streptomyces* to suppress blast indicates the presence of bioactive compounds in which few have been identified. Several antibiotics that have been isolated from various *Streptomyces* strains include Oligomycin A, Rapamycin, Pyrroles (Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-) and other compounds which have all been observed to inhibit the growth of *P. oryzae* and protect plants from phytopathogenic fungi [13] [73] [74]. Knowledge on these bioactive compounds is essential to the development of agricultural fungicides with a specific pathogen target and reduction of environmental impacts [75].

There is a consensus among the literature that several antagonistic mechanisms allow *Streptomyces* strains to exhibit their antifungal properties. *Streptomyces spp.* have the ability to colonize plant roots, produce antibiotics, and synthesize extracellular proteins. They produce spores which support their survival in different and extreme soil environments [76]. In addition, studies have detected the presence of antibiotics such as geldanamycin and nigericin in soil, suggesting the role of these antibiotics in inhibiting the pathogen [77] [78]. They also release chitinases and glucanases which destroy the cell walls of the fungus [79]. These traits allow *Streptomyces spp.* to successfully suppress rice blast, but further studies are needed to elucidate their mechanisms.

As seen in **Table 3**, while previous studies have demonstrated efficacy in vitro conditions, results may vary for greenhouse or field conditions due to differing environmental conditions. Several factors such as organic matter, pH, nutrient level, and soil moisture may also affect the efficacy of bacterial strains for biological control. In order to maximize returns for application, strains should be isolated from and applied to sites that share environmental conditions. Equally important, the formulation and method of application (soil inoculation, seed inoculation, vegetative part inoculation) also deserve serious attention to maintain the efficiency of *Streptomyces spp.* against rice blast in field trials. It is also of note that while commercial *Streptomyces* biocontrol agents have been developed for other plant diseases, they have yet to be formulated for the control of rice blast [80] [81].

Table 3. Summary of previous experiments on using streptomyces strains to control blast disease.

Agent	Type of experiment	Results (percent of inhibition of *P. oryzae*)	Study
Streptomyces philanthi RM-1-13	*In vitro* experiment using dual culture method	88.73% mycelial growth inhibition of *M. oryzae*	[82]
S. vinaceusdrappus	*In vitro* experiment using dual culture method	53.5% mycelial growth inhibition of *M. oryzae*	[76]
S. globisporus JK-1	Greenhouse experiment	88.3% fungal control compared to inoculated control	[21]
S. flavotricini	*In vitro* experiment using dual culture method	40 mm inhibition zone	[83]

4. Future Perspectives

Rice blast is a prevalent and destructive disease in the paddy fields of Vietnam and other countries. The issue will only require more extensive efforts in response to the effects of climate change. As elaborated in previous sections, it is clear that methods other than chemical fungicides, including the use of botanicals or plant growth-promoting bacteria, are more sustainable alternatives compared to more conventional chemical-based methods and can have similar effectiveness. Accordingly, the development of natural products, and especially microbial biocontrol agents, as alternative solutions to manage plant diseases has gained traction in recent years. Due to their active microbial populations, they can also reproduce and multiply effectively using their ecological position. In analyzing their mechanisms, studies have proposed that *Streptomyces spp* can survive in a wide range of soil conditions while producing spores that assist with survival even in extreme weather conditions. Other benefits include cost-effectiveness, long lifetime, and environmentally compatibility with the environment and living organisms.

However, new studies are required to confirm and evaluate the biocontrol potential of *Streptomyces* strains, especially field experiments because laboratory experiments are performed under strictly controlled conditions. In addition, biological control is a slow and continuous process that demands time and effort to select appropriate strains for use and integrate into the system. It can be seen that the use of *Streptomyces* have high efficacy against blast pathogens and can be implemented.

However, a series of steps must be followed before *Streptomyces* strains are widely applied in Vietnam. Testing of complex environmental conditions of the local area must be conducted to select strains with consistent biocontrol activity. In addition, the method of application must also be assessed to appropriately deliver an optimized formula that could yield the highest efficiency. Additionally, the antifungal mode of action of *Streptomyces* must be further assessed to avoid risks of spreading dangerous metabolites for human and animal health in surrounding environments. Besides *in vitro* testing for antifungal activity, this can be completed through bioassays on fermentation extracts to identify metabolites responsible for antifungal properties. Purification and chemical analysis should also be required to test purified compounds before being applied for use. In summary, the steps to isolate, formulate, and apply *Streptomyces* must be thoroughly reviewed to ensure optimal efficiency for rice blast control.

To guide future implementation of *Streptomyces* spp. and other emerging, sustainable management strategies, there also needs to be effective communication between the farmers and local governments in promoting this technology, requiring active cooperation between small-holder farmers, mass media, as well as local authorities to distribute and facilitate the flow of information. Methods that would help with information distribution include distributing pamphlets, leaflets in Vietnamese language as well as hosting group meetings to further discuss their implementation in rice fields. Local governments should consider developing necessary policies to facilitate technology transfers between ecological workers and rural farmers to ensure that biocontrol strategies are properly adopted. Major constraints to the adoption process include expensive labor costs and time factors that may not have been accounted for. Thus, implementation will also require feasibility studies to determine the overall effectiveness and efficiency of implementing biocontrol using *Streptomyces*.

In addition, integrating many solutions including cultural practices, resistant cultivars, chemical-based methods, with biocontrol will be necessary in designing an approach that fully considers future climate conditions which may influence the biological characteristics of rice blast and its spread. This can be achieved through cooperation among researchers from many areas to assess vulnerability and construct warning systems to minimize effects of rice blast on the cropping system. For example, understanding host-pathogen interactions will be crucial to establishing necessary measures that can effectively respond to climate change effects or new disease introductions. Therefore, while the biocontrol agent *Streptomyces* spp. has been identified as an effective, albeit underexplored, way to combat rice blast disease, a successful control of blast disease and management in Vietnam will necessitate the coordination between different groups, resources, and people to successfully integrate it into current farming systems of Vietnam.

5. Conclusion

Based on our findings, it can be concluded that rice blast disease has many implications for the agricultural sector. The use of chemical control has negative environmental impacts and alternatives should be considered. While the use of resistant varieties is a plausible option, the fungus can easily mutate to overcome such resistance, requiring new technologies to prevent this. Thus, biocontrol using *Streptomyces* stands as a promising alternative with many benefits including cost, safety, and duration. As an excellent candidate to be integrated for use in future agricultural plans, more work is still needed to examine isolation and application methods to maximize its efficiency. As well, future field trials are needed to confirm and establish its efficiency.

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Conflicts of Interest

The author declares no conflicts of interest.

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