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REVIEW

Ecological Implications of Fungicide Use in Rice Blast Control: A Review of International In *Vivo* Trials

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ABSTRACT

Rice blast, caused by *Pyricularia oryzae*, is one of the most damaging fungal diseases affecting rice production worldwide, with major implications for food security and agroecosystem stability. Chemical control, particularly the use of tricyclazole, has been widely adopted in many rice-growing regions due to its specific action on the pathogen's melanin biosynthesis pathway. This review compiles and analyzes findings from *in vivo* field studies conducted in Asia, Africa, Europe, and Latin America to assess the agronomic efficacy, environmental risks, and sustainability of tricyclazole-based treatments. Results consistently show that tricyclazole provides effective protection against both leaf and panicle blast, contributing to improved plant health and enhanced grain yield. However, long-term reliance on this fungicide presents challenges, including the potential development of pathogen resistance, residue accumulation in rice grains and soil, and ecotoxicological impacts on non-target organisms in integrated rice–aquatic systems. The review emphasizes the importance of integrated disease management approaches that combine fungicides with genetic resistance, crop rotation, optimized fertilization, and ecological practices. Special attention is given to sustainability issues, highlighting the need for the rotation of active ingredients, residue monitoring, and ecological risk assessments. By providing a balanced perspective on

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both the benefits and limitations of tricyclazole, this paper supports more informed decisions in rice disease management and contributes to the transition toward more resilient and environmentally responsible agricultural systems.

Keywords: Rice; Blast; *Pyricularia oryzae*; Tricyclazole; Fungicides; Chemical Control; Efficacy; Resistance
JEL Codes: Q16; Q57; O13

1. Introduction

Rice (*Oryza sativa* L.) is the primary food source for a large portion of the world's population. China is the leading producer, with more than 214 million tons harvested from approximately 30 million hectares in 2021 [1]. Rice blast, a devastating fungal disease caused by *Pyricularia oryzae* Cavara (also known as *P. grisea* or its sexual form *Magnaporthe grisea*), remains a major threat to global food security by significantly compromising rice productivity [2]. Considered one of the most devastating diseases affecting rice, it can cause yield losses of more than 50% in cases of moderate infection [3]. The scale of these losses is such that it could deprive more than 60 million people of food each year [4]. In addition to its impact on yield, blast disease alters the physical properties of rice grains, thus representing a major constraint to sustainable production [5].

Tricyclazole is a systemic fungicide widely used in numerous rice-producing countries to control rice blast disease. Its effectiveness has been demonstrated through extensive scientific research conducted in regions such as Asia, Europe, Africa, and South America [6,7]. Tricyclazole acts at multiple levels of the host–pathogen interaction. It interferes with the fungal physiological processes by inhibiting key mechanisms of pathogenesis, such as the activity of hydrolytic enzymes and the secretion of pathotoxins [8]. Additionally, it may stimulate the production of plant metabolites that function as defense elicitors. A key target of Tricyclazole is the melanin biosynthesis pathway in *Pyricularia oryzae*, as melanin is essential for the development of the appressorium, a structure required for host penetration. The biosynthetic route involving 1,8-dihydroxynaphthalene polymers was initially elucidated using melanin-deficient mutants of Verticillium dahliae, and similar mechanisms have since been confirmed in rice blast pathosystems [9,10].

Tricyclazole prevents two reactions in the melanin biosynthesis pathway of *V. dahliae* and *P. grisea* [11,12]. According to Tokousbalides and Sisler [13], this fungicide reduces pathogenicity by inhibiting the synthesis of polyketide-derived toxins. The inhibition of *P. grisea* development on treated plants, one day before inoculation, suggests that Tricyclazole probably acts on other levels of the host-parasite relationship by activating resistance mechanisms (under whose action the parasite would produce more elicitors that would trigger the defense reaction). The mechanisms of such action are not yet fully established [13]. According to Froyd et al., Tricyclazole acts on host resistance mechanisms. According to this hypothesis, the fungicide disrupts plant resistance in such a way that the defense response is activated, similar to what is observed in genetically resistant plants [14].

The impact of fungal diseases on cereal crops, particularly rice, can be understood through the theory of agricultural production under health uncertainty, which highlights how pathogens such as *Pyricularia oryzae* compromise plant physiology, thereby reducing yields and farm profitability [15,16]. Fungicides, as health inputs, aim to restore this production potential, but their use raises environmental concerns and risks of resistance [17]. The economic efficiency of these treatments is based on a causal chain that ranges from reducing disease severity to improving yield and gross income per hectare, although this relationship is influenced by factors such as formulation type, application timing, climatic conditions, and varietal resistance. In this context, integrated rice disease management appears to be a balanced approach, aiming to reconcile agronomic performance, economic profitability, and ecological sustainability-perspective at the heart of this review, which explores the interactions between fungicide treatments, ecosystem impacts, and production outcomes [18,19].

This work falls within the theoretical framework of integrated disease management in agriculture, combining economic (efficiency of sanitary inputs), ecological (impact on non-target organisms, bioaccumulation), and phytopathological (fungicide modes of action and resistance dynamics) approaches. The theory of agricultural production under sanitary uncertainty explains how disease severity reduces productivity and how sanitary inputs, such as fungicides can restore yield, with direct economic implications for income per hectare. This review provides an overview of field studies on the use of tricyclazole for managing rice blast in various rice-growing regions. It focuses on the fungicide's effectiveness, whether used alone or in combination with other molecules, in controlling leaf and panicle blast, enhancing yield, and improving grain quality. Application methods, such as seed treatment and foliar spraying are assessed. The review also addresses the importance of proper dosage, regulatory compliance, and residue monitoring in rice and soil. In addition, it explores the fungicides' modes of action, agronomic impacts, and limitations, aiming to support more effective and sustainable disease control strategies.

2. Background

Rice (*Oryza sativa* L.), belonging to the Poaceae family, is the main cereal consumed by more than half of the world's population, particularly in Asia, Latin America, and tropical Africa. There are three main varietal groups: *Indica, Japonica,* and *Javanica*, as well as two domesticated species: *Oryza sativa* (Asian) and *Oryza glaberrima* (African). Native to the tropical and subtropical regions of South Asia and Southeast Africa, rice has long shaped societies and diets. It is now grown in a variety of environments, although it prefers hot, humid, and flooded conditions [20–23]. In Morocco, rice cultivation began in the 1930s and expanded significantly from 1949 onwards, particularly in the Gharb region. Between 2003 and 2019, the area under cultivation increased by 35%, and production grew by 48%. Unlike wheat and corn, all rice produced is intended for human consumption. However, this crop remains susceptible to several constraints, including fungal diseases such as blast disease [24,25].

2.1. Rice Blast and the Pathogen

A major biotic constraint on rice production worldwide is blast disease, a potentially highly destructive fungal disease caused by the fungus *Magnaporthe oryzae* (syn. *Pyricularia oryzae*), which is highly adaptable and genetically variable [26–28]. Rice blast infects the rice plant only at the aerial sections (i.e., leaves, nodes, and panicles) and causes oval lesions on the plant that interrupt photosynthesis reducing yield by over 90% (**Figure 1**) [2–28]. In places susceptible to environmental conditions and factors conducive to its ontogenetic advancement, blast can be produced in polycyclic potential for dissemination and growth, especially in the presences of warm temperatures and high humidity (> 80%, 15–25 °C) [29]. Abundant use of nitrogen fertilizers, and multiple existing strains of pathogens further increasing the currency of potential incidence of the disease [30]. Symptoms of rice blast logically start as spindle-shaped spots that are gray or brown in color toward the leaf blade that expand in area, while necrosing all its actuated body parts initially. Its biology has both sexual and asexual stages of development and the mean agent of spread during these stages is via conidia [31]. **Figure 2** presents a mind map of this fungus life cycle at multiple stages from spore germination through a host invasion and colonization.

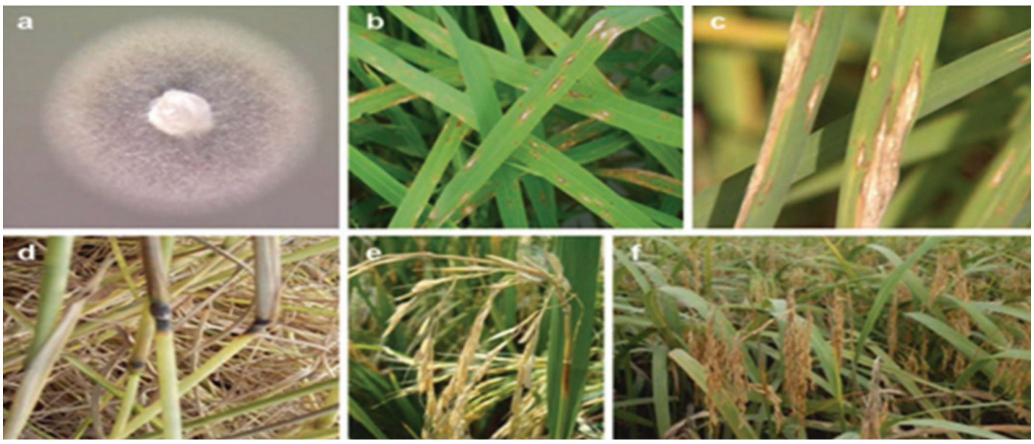

Figure 1. Symptoms and pathogen of rice blast: (**a**) *Pyricularia oryzae*, the causal agent of rice blast; (**b**) minor blast lesions on leaves; (**c**) characteristic elliptical lesions on leaves; (**d**) blast disease on nodes; (**e**) blast disease on panicles; (**f**) rice field infected with blast disease [32].

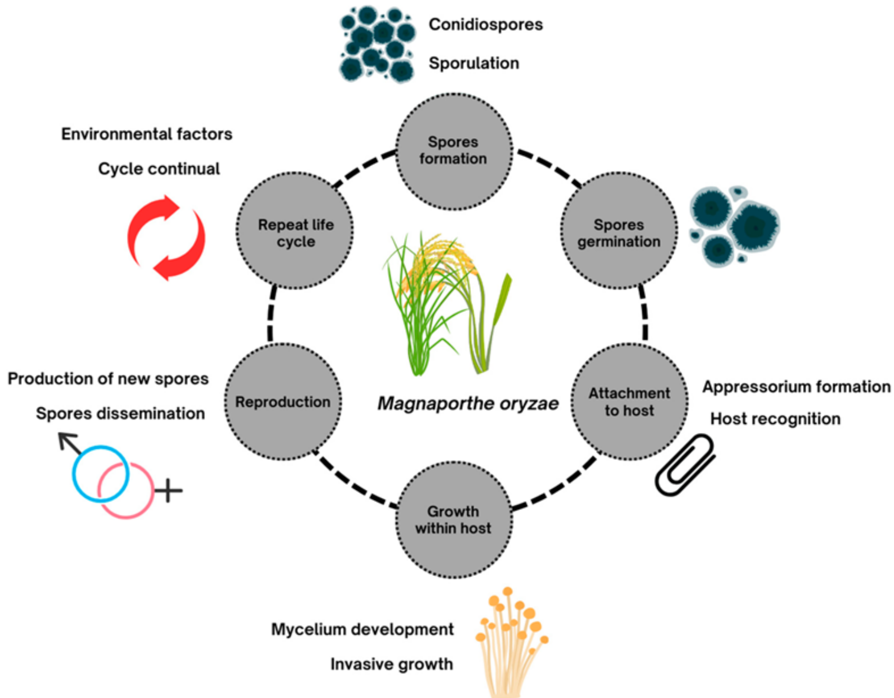

Figure 2. Mind map diagram showing the life cycle of *M. oryzae* [8].

The notorious wide-ranging distribution of rice blast occurs in over 85 countries and continues to pose a recurring threat to food security, with yield losses ranging from 10% to 30% during typical outbreaks of Bacillus, and up to 100% during severe epidemics [33,34]. The impact of the rice blast disease agent, *Magnaporthe oryzae* [*B. oryzae*] affects other diverse host plants not only among rice (*Oryza sativa* L.) but also on a range of economically important cereals including wheat, maize, barley, and finger millet as well as an array of ornamental and weedy grasses [35]. The diversity of host plants important to economy enhances the survivability of the fungus in agroecosystems and makes effective control more difficult [36]. While there are limited studies to examine host and pathogen interactions and infection processes related to rice, we are still deficient of knowledge of this pathogen outside of host rice, including its transmission to other species [37]. The pathogen's resilience and adaptability underline the urgent need for integrated disease management practices combining genetic resistance, cultural methods and chemical control [38].

2.2. Chemical Control of Rice Blast

Chemical control remains one of the most used and effective management methods for rice blast, especially when resistant varieties are no longer effective. Japan was one of the early leaders in managing rice blast through chemical control. Initially, copper-based fungicides were widely applied due to their effectiveness in controlling rice blast. However, problems began to emerge with copper fungicides, including their phytotoxic effects on rice, effects on human health, and effects on soil the microbial community [39,40], which led to the exploration of less harmful materials [41].

In time, both copper fungicides and phenylmercuric acetate (PMA) were available, and while PMA was safer for human and plant health, it improved disease control in rice blast [42,43]. Then organophosphorus compounds were evaluated and were widely adopted in rice blast control programs [43]. Unfortunately, by the late 1970s, reported instances of resistance in *Magnaporthe oryzae* to organophosphorus fungicides been reported. This prompted new strategies to eliminate the possibility of developing resistance to these fungicides, such as using fungicide rotations or combinations, rather than continuous applications of a single product [44].

These tools set the stage for further universities to create new families of fungicides with varying modes of action, including ergosterol biosynthesis inhibitors (EBIs), melanin biosynthesis inhibitors, and anti-mitotics [45,46]. The extensive use of modern fungicides has reduced the losses caused by *M. oryzae* and improved rice yield and quality worldwide. However, this chemical pressure has created an aggressive strain of the pathogenic population; this illustrates the need for continued innovation in fungicide development. The formation of melanized appressoria, which are structural specializations required for the penetration of *M. oryzae* through the cuticle of the rice leaf[47] is a key target in the fungal infection process. Thus, much of the research has attempted to identify melanin biosynthesis inhibitors (MBIs), in particular inhibitors of the DHN, and DOPA pathways. To date, two main classes of MBIs have identified scytalone dehydratase inhibitors (MBI-D), and polyhydroxynapthalene reductase inhibitors (MBI-R). These usually include fungicides tricyclazole, pyroquilon, and phthalide, which have all been widely used for over 30 years without field resistance. However, some resistant mutants have been confirmed only under laboratory conditions in China[48].

Central to these efforts, tricyclazole now occupies the primary position in current chemical control practices against rice blast. Systemically used in this way, tricyclazole is a member of the triazolobenzothiazole family of chemicals and functions by inhibiting the biosynthesis of melanin in the appressoria, thereby preventing the fungus from penetrating the host. It exhibits excellent residual action with a unique efficacy (no field resistance is reported as of today)[49,50]. Importantly, it is specific to fungi using the DHN melanin biosynthetic pathway, so it has highly specific action against *P. grisea*. With a chemical formula of $C_9H_7N_3S$ (i.e., one triazole ring, one benzothiazole, and one methyl branch at 5-position), tricyclazole shows high molecular stability and long binding to the enzymes of fungi and plant, however with low solubility to water (1.6 g/L at 25 °C), but reasonable solubility to methanol (25 g/L) and acetone (10.4 g/L). It is stable to heat (54 °C) and UV light, however is rapidly hydrolyzed in very strong alkaline conditions. All these physicochemical properties affect the persistence of it in the environment and how well it remains effective in rice blast control practices[51].

3. Related Work

Rice blast, which is caused by Magnaporthe grisea, is one of the most significant challenges to rice production. This research focused on evaluating the previously demonstrated control of rice blast with tricyclazole, a widely used fungicide, either alone or in combination with thifluzamide. This innovative method of application either as a single/in fused fungicide to the seedling trays resulted in accepted control of this plant disease, while potentially providing a greater benefit to the application process. Finally, tricyclazole/thifluzamide mixture ratio of 1:2 demonstrated interaction resulting in a significant synergistic interaction for the inhibition of mycelial growth of the blast pathogen with a synergistic ratio of 2.17. The products showed excellent control in the field, with the mixture reducing the disease index by over 83%, which was comparable to the effect of applying two foliar applications of tricyclazole alone. This method of application not only provided effective phytosanitary control measure but also reduced the labor effort and increased total grain yield by a sizeable margin up to 7429.73 kg/ha. Therefore, applying tricyclazole to seedling trays particularly with the introduction of thifluzamide to accelerate the integration into overall rice blast management method, may be an effective and alternative strategy. Future research needs to assess the threshold of efficacy in product application on the seedling trays and the long term benefit to plant health and environmental safety[52].

Numerous studies have been conducted to examine the effects of pesticides on non-target aquatic organisms in farming systems with integrated aquatic systems. More recently, one study examined the relation of a specific pesticide, tricyclazole - which is a fungicide widely used for the control of rice blast - in a rice crab co-culture system with the Chinese mitten crab (Eriocheir sinensis). The research showed that tricyclazole did not demonstrate acute toxicity (LC50 > 100 mg/L); however, it was found to bioaccumulate in the crab's hepatopancreas (an organ responsible for detoxifying and metabolizing compounds). Chronic exposure impacts included impaired lipid metabolism, immune function suppression, and molting reciprocation frequency being altered in females who were more sensitive while weight gain was raised by the compound. While the pesticide altered molting duration and increased weight gain in crabs, concerns about growth and development were raised. The risk to food safety was assessed as very low, but potential repercussions on ecology and the economy may be large; therefore more surveillance of tricyclazole was recommended to allow better data on the health of aquatic organisms and provide a more sustainable agroecological model for integrated aquaculture-agriculture systems [53].

To meet the demand for fast and portable detection of tricyclazole (TRI) residues in rice, Liu et al. (2024) developed a paper-based lateral flow immunochromatographic assay (LFIA) using gold nanoparticles [54]. A specifically targeting monoclonal antibody (mAb), with an IC_{50} of 1.61 ng/mL, was created using optimized hapten derivatization plans to enhance immunogenicity. The final sensor reached limits of detection of 6.74 μg/kg in polished rice and 13.58 μg/kg in brown rice with recoveries of 84.6% through to 107.4%. Outstandingly, sample preparation requirements were minimal, and the developed sensor demonstrated strong correlation with LC-MS/MS reference methods for quantitation, as well as other low-cost, user-friendly field products. The authors noted that compared to traditional instrumentation - LC-MS, surface-enhanced Raman spectroscopy, or colorimetric and other types of assays - that can be time-consuming and require complex sample preparation and expensive machinery, their LFIA offered substantial advantages to effectively implement field work in agricultural fields. With extensive environmental monitoring of TRI across the globe and the ultrasonic toxicity of TRI evidenced with endocrine-disruption, reproductive-related toxicity, mutagenicity, and bioaccumulation, this makes portable diagnostic tools extremely valuable for food safety and environmental monitoring. As opposed to previous studies focusing exclusively on the efficacy of tricyclazole, this review adopts an integrated approach that considers agronomic efficacy, ecological impacts (bioaccumulation, chronic toxicity), and agroecological prospects in various of international contexts.

4. Comparative Effectiveness of Fungicides in Different Countries

Field trials conducted in several agroecological zones enabled a comparative evaluation of several fungicide treatments applied alone or in combination against rice blast, caused by the fungus *Pyricularia oryzae*. In all studies (**Table 1**), it was clear that tricyclazole-based treatments, whether applied as seed treatment or foliar spray, provided the best protection against leaf and panicle blast. Even better results were obtained using seed treatment with 3 g/kg tricyclazole plus a foliar spray at 0.6 g/L. This integrated strategy resulted in the lowest disease severity index (DSI) values for both leaf and panicle blast: 15.37% for leaf blast and 10.00% for panicle blast. The latter result represents a significant improvement. These results provide a basis for concluding that, when both modes of application can be used, rapid and effective protection of aerial tissues against *P. oryzae* is likely to be enhanced by the systemic protective effects of tricyclazole seed treatments. Furthermore, the results show that when a tricyclazole-based product is applied with other fungicides, such as isoprothiolane or carbendazim, the synergistic effects can be considerable. The treatment of carboxin with thiram as a seed treatment followed by a foliar spray of isoprothiolane at 1.5 mL/L should be considered a viable alternative, particularly if the use of tricyclazole is subject to restrictions or if antifungal rotation is necessary [55].

Table 1. Comparative Efficacy of Fungicide Treatments Against Rice Blast Across Different Regions.

Treatment Type	Treatment Details	Results	Bibliographic References
Seed treatment only	T1: Tricyclazole 75 WP at 3 g/kg of seed T2: Carboxin 37.5% + Thiram 37.5% at 2.5 g/kg of seed	Initial disease control; not sufficient alone for full blast management.	(India, 2021) [55]
Seed treatment + foliar spray	T3: T1 + Tricyclazole 0.6 g/L T4: T1 + Hexaconazole 5 SC at 2 mL/L T5: T1 + Carbendazim 1g/L T6: T1 + Isoprothiolane 1.5 mL/L T7: T2 + Tricyclazole 0.6 g/L T8: T2 + Hexaconazole 2 mL/L T9: T2 + Carbendazim 1g/L T10: T2 + Isoprothiolane 1.5 mL/L	T3 was the most effective for both leaf and neck blast (PDI: 15.37 for leaf blast, 10.00 for neck blast). T10 was also effective (PDI: 18.89 for leaf blast, 12.61 for neck blast). Statistically significant results at P = 0.05. Tricyclazole-based treatments consistently outperformed others.	(India, 2021) [55]
Foliar spray only	Tricyclazole 0.5 g/L (2 sprays) Isoprothiolane 2 mL/L (3 sprays)	Tricyclazole reduced leaf blast severity to 9.4% and AUDPC to 81.87. Isoprothiolane was less effective. Disease progression rate (r) was lowest with tricyclazole (0.01–0.04). High efficacy also observed on panicle blast control.	(Egypt, 2018) [56]

Table 1. *Cont.*

Treatment Type	Treatment Details	Results	Bibliographic References
Foliar spray	Various fungicides including Tricyclazole, Trifloxystrobin+Tebuconazole	Tricyclazole and Trifloxystrobin+Tebuconazole provided the best control for panicle and collar blast. Tricyclazole led to grain yield increases >310% compared to untreated control.	(Brazil, 2018) [57]
Foliar and soil treatment	Tricyclazole, Hinosan, Phosvel – applied as seedling spray and soil treatment	Tricyclazole (0.10%) was most effective. Delay in symptom expression indicates extended incubation period and systemic effect. Superior to Hinosan and Phosvel for both foliar and panicle blast.	(Malaysia, 1982) [58]
Foliar spray	Eleven fungicides including Tricyclazole, Carbendazim, Ediphenphos	Tricyclazole showed highest disease suppression (35.62%), best grain yield (43.05% increase). Also increased plant height, tiller number, panicle length.	(India, 2016) [59]
Foliar spray	Tricyclazole + Zinc EDTA, Picoxystrobin + Tricyclazole	Highest leaf and neck blast reduction with Tricyclazole + Zinc EDTA (60.06%). Grain yield significantly improved.	(Bangladesh, 2023) [60]
Foliar spray	Tricyclazole with two doses (300 and 750 ppm)	90 to 100% inhibition of *P. grisea* sporulation and significant reduction in disease severity (curative and preventive effect). For plants treated with a dose of 750 ppm, the percentage reduction in disease reaches 90.32% in preventive treatment. This percentage does not exceed 72.99% in curative treatment. This dose inhibits the sporulation of *P. grisea* on leaves by 90–100% in both types of treatment.	(Morocco, 2004) [61]
Single foliar application	Single foliar application of Tricyclazole at 750 ppm on 3–4 leaf stage rice plants	Tricyclazole at 750 ppm achieved 100% reduction in blast severity 8 and 15 days after application and maintained high protection at 22 days (81.5%) and 29 days (80%). No phytotoxicity observed. Treatment was significantly more effective than the untreated control and provided persistent protection throughout the vegetative phase.	(Morocco, 2017) [62]

In Egypt, trials also demonstrated that tricyclazole was superior to isoprothiolane. Tricyclazole successfully maintained the severity percentage below 10% and had a significantly lower area under the disease progression curve, 81.87% compared to 20.5% for isoprothiolane. The disease progression rate was minimal, ranging from 0.01 to 0.04 for tricyclazole, suggesting that it was very successful in disrupting the infectious cycle of the pathogen, particularly during the vegetative phase. Although isoprothiolane was effective, its level of activity was slower and its spectrum of action narrower, with severity levels reaching 20.5% by the end of the season. This suggests that it has a weaker fungistatic effect [56].

In Brazil, the experiment included a broader spectrum of fungicide combinations. Regarding panicle blast, only the tricyclazole and trifloxystrobin + tebuconazole combinations provided acceptable levels of control. The tricyclazole and trifloxystrobin + tebuconazole treatments not only reduced the disease incidence by 50% compared to the untreated controls, but also realized the largest increases in grain yield—tricyclazole realized yields of up to 9903.79 kg/ha, which represented >300% yield increase. This underscores the direct impact of effective disease management on crop productivity, especially when the reproductive organs of the rice plant are protected [57].

In Southeast Asia (particularly Malaysia), the trials included both foliar sprays and soil treatments. Tricyclazole outperformed conventional fungicides like Hinosan and Phosvel, whether applied as a preliminary seedling spray or a soil treatment. The tricyclazole treatment also increased the incubation period of *P. oryzae*, which suggests that in addition to preventative action, a systemic action was provided for a longer period after and possibly before treatment. This is especially beneficial in nursery operations where early disease prevention is critical to disease suppression throughout its life cycle [58].

Furthermore, in another study in India, the results obtained with tricyclazole on a variety of Basmati rice, which is highly susceptible to blast disease, provide further evidence of the effectiveness of this molecule. Tricyclazole showed a disease severity index of 35.62%, well below that of other molecules, and improved yield-related characteristics, such as the number of tillers, panicle length, and grain weight. The increase in yield is likely due to the overall healthier physiological condition of the treated plants, which maintained a photosynthetically active leaf area at all selected growth stages [59]. In Bangladesh, innovative formulations of tricyclazole with other active ingredients or micronutrients like zinc (e.g., Tricyclazole 75% WP + Zinc EDTA 12%) showed even more promising results. This treatment reduced the incidence of leaf and neck blast by more than 60% and gave the highest grain yield (5.36 t/ha), much more than the untreated plots (3.42 t/ha). This further highlights the value of combining fungicidal protection with micronutrients to strengthen plant resilience and defense metabolism [60].

In Morocco, an *in vivo* study conducted by El Abdellaoui et al. [61] demonstrated the strong efficacy of tricyclazole against *Pyricularia grisea* under controlled greenhouse conditions. The application of tricyclazole at the homologated dose of 750 ppm resulted in a significant reduction in disease severity and inhibited the sporulation of the pathogen by 90 to 100%, depending on the treatment timing. These findings confirmed both curative and preventive effects when the fungicide was applied 24 h before artificial inoculation. The study highlights the potential of tricyclazole as a reliable systemic fungicide for integrated disease management in Moroccan rice systems, especially under high infection pressure. Another study conducted by Mouria et al. [62] clearly demonstrated the effectiveness of Tricyclazole against rice blast caused by *Pyricularia oryzae*. A single foliar application of Tricyclazole at 750 ppm on plants at the 3–4 leaf stage resulted in a total (100%) reduction in disease severity eight days after treatment. This efficacy remained at 100% for up to 15 days, then remained high with a reduction of 81.5% at 22 days and 80% at 29 days after treatment. No phytotoxic effects were observed, even at higher doses. These results indicate that tricyclazole, applied at 750 ppm, is a highly effective and long-lasting preventive treatment option against leaf blast in rice during the vegetative phase.

The relationship between blast severity and economic losses is explained by a direct drop in yield, degradation of grain quality, and increased management costs. Economic models show that an effective fungicide can reduce these losses, but at the cost of environmental risk, hence the interest in an integrated approach. Indeed, the yield gains associated with the use of tricyclazole translate into a significant improvement in the profitability of rice-growing systems. When the cost of treatments is taken into account, the benefit-cost index is clearly in favor of integrated treatments, especially when they reduce the total number of interventions. The economic sustainability of this strategy is further enhanced by the fact that tricyclazole has yet to show widespread resistance in the field. In synthesis, tricyclazole offers the best foliar and panicular protection, particularly when combined with a seed treatment. Its efficacy has been demonstrated in all the agroecological contexts examined, although enriched formulations (such as zinc, molecular associations) show potential for further improvement.

5. Most Effective Fungicides: Comparison and Interpretation

Overall regions evaluated, tricyclazole has provided the most effective control of rice blast disease occurring on both the leaf and panicle levels [63,64]. The tricyclazole compound is unique in its mode of action against the pathogen *Magnaporthe oryzae*, specifically its action on melanin biosynthesis [65]. Melanin is an important pigment for the pathogenic virulence mechanism [66]. Thus, by inhibiting melanin, tricyclazole interrupts the ability of the pathogen to form the infection structure, which limits its ability to penetrate or colonize plant tissue [67]. This specificity gives tricyclazole a long-lasting and unique efficacy that is relatively uncommon among other fungicide classes. Likewise, other fungicide classes, such as isoprothiolane, strobilurins and triazoles provide adequate improvement, especially when combined or alternated with tricyclazole [68]. Isoprothiolane primarily disrupts fungal lipid synthesis, strobilurins block the mitochondrial respiration of the fungus and triazoles target sterol biosynthesis that is required for the fungal cell membrane [69]. The diversity of action mechanisms supported the ability to design phytosanitary strategies by the locality while minimizing the risk of resistance formation [70].

6. Applied Ecology and Integrated Management of Rice Diseases

6.1. Relationship to Sustainable Management of Agroecosystems

Fungicides used to control *Pyricularia oryzae* differ in their biochemical mechanisms of action, which determine their efficacy, persistence, and potential for resistance development. Tricyclazole, which has been extensively studied, acts as an inhibitor of melanin biosynthesis (MBI-R), a metabolic pathway essential for the formation of appressoria, structures that enable fungal penetration into plant tissues [71]. By inhibiting this step, tricyclazole blocks infection at its initial stage. Strobilurins, such as trifloxystrobin, target mitochondrial respiration, while triazoles (tebuconazole, propiconazole) inhibit sterol biosynthesis in the cell membrane. Isoprothiolane interferes with membrane lipid synthesis [72]. The effectiveness of these products depends on the timing of application, their mode of penetration (systemic or contact), and their compatibility with local agricultural practices. Their combined use, particularly the combination of tricyclazole + strobilurin or tricyclazole + carbendazim, has shown interesting synergistic effects, with a significant reduction in the disease severity index [64].

6.2. Relationship to Sustainable Management of Agroecosystems

An integrated rice disease management approach involves the complementary use of chemical, genetic, and cultural methods [73]. The results of this review suggest that the most effective strategy combines seed treatment (e.g., tricyclazole 3 g/kg) followed by foliar sprays (e.g., tricyclazole 0.6 g/L or isoprothiolane 1.5 mL/L). This dual treatment provides prolonged protection, reduces the number of applications required, and limits the spread of the disease.

At the same time, it is essential to incorporate:

- partially resistant varieties,
- crop residue management,
- an appropriate sowing schedule,
- balanced fertilization (avoiding excess nitrogen).

This integrated approach optimizes the effectiveness of chemical treatments while minimizing their environmental and economic impact.

6.3. Need for Fungicide Rotation and Rational Combinations

Repeated treatments with a single molecule or chemical family promote the emergence of resistant fungal populations [74]. It is therefore essential to alternate between fungicide families with different modes of action (triazoles, strobilurins, benzimidazoles, etc.). Annual rotation and occasional combinations of different molecules (e.g., tricyclazole + mancozeb, or trifloxystrobin + tebuconazole) reduce selection pressure and prolong the effectiveness of the products. The implementation of integrated treatment schedules, validated by local epidemiological data, is a major lever in the sustainable management of pyriculariosis [75,76].

7. Sustainability, Ecotoxicology, and Environmental Risks

7.1. Fungal Resistance: Factors and Solutions

Cases of resistance to tricyclazole have been reported, particularly in Japan, linked to mutations in the genes encoding enzymes involved in the melanin biosynthesis pathway [8–77]. These mutations reduce the product's effectiveness without altering the pathogen's viability. Repeated use of a single fungicide, without rotation or diversification, accelerates these adaptive phenomena [78].

To address this risk, it is essential to:

- diversify active ingredients,
- adopt flexible treatment protocols,
- monitor the evolution of fungal populations through phytopathological surveillance networks.

The integration of biopesticides, biological treatments, and resistant varieties is a promising alternative for reducing selection pressure.

7.2. Potential Impacts on Aquatic Biodiversity

Recent research has highlighted the bioaccumulation of tricyclazole in non-target aquatic organisms, particularly the Chinese mitten crab (Eriocheir sinensis), which is commonly found in integrated rice farming systems [78]. Although acute toxicity remains low (LC50 > 100 mg/L), chronic effects include metabolic alterations, molting disruption, immunosuppression, and potential impacts on reproduction. Females are more sensitive, which may have consequences for population dynamics. These observations highlight the importance of limiting spray drift, avoiding treatments before rice fields are flooded, and prohibiting the use of tricyclazole in integrated agro-aquaculture systems without prior impact assessment [53].

7.3. Bioaccumulation and Soil/Water Pollution

Tricyclazole, which is poorly soluble in water but stable in neutral environments, can accumulate in rice field sediments and persist for several weeks [79]. Repeated use increases residual concentrations in grains, straw, drainage water, and soil, exposing soil organisms (worms, microflora) to sublethal toxicity risks [80].

Studies on residues show the need to:

- reduce the doses applied,
- comply with pre-harvest intervals (PHIs),
- and monitor residual concentrations in agricultural products (rice, straw) using modern detection methods (portable sensors, LC-MS/MS).

8. Agroecological Perspectives

8.1. Relationship to Sustainable Management of Agroecosystems

The fight against pyriculariosis should not be limited to a curative approach. It is part of an ecosystemic vision of crop health, in which soil, water, functional biodiversity (entomofauna, microflora), and agricultural practices interact. Agroecological management aims to strengthen the resilience of agroecosystems to better cope with pathogens while limiting the use of chemical inputs [81].

8.2. Towards a Reduction in Chemical Inputs

To reduce the use of synthetic fungicides, several complementary strategies can be implemented [82]. One effective approach is the use of resistant or tolerant crop varieties, whether obtained through classical crossbreeding techniques or more advanced methods such as CRISPR gene editing. Additionally, optimizing fertilization practices helps prevent nitrogen imbalances that could otherwise promote the development of plant diseases [83]. Crop rotation and proper management of crop residues also play a key role in disrupting the survival cycles of pathogens. Furthermore, the adoption of biofungicides derived from natural extracts—such as garlic, thyme, or neem—offers an environmentally friendly alternative [84].

8.3. Towards Smart and Eco-Friendly Rice Farming

Modern rice farming is increasingly embracing innovative and low-impact solutions aimed at enhancing sustainability [85]. Among these, the development of biopesticides derived from antagonistic microorganisms such as Trichoderma and Bacillus subtilis, or from plant extracts, offers promising alternatives to conventional chemicals [86]. Technological tools are also gaining ground, including portable smart sensors that enable rapid detection of tricyclazole residues in rice grains, thus ensuring food safety and compliance. In parallel, genomic approaches are being used to assist in the selection of resistance genes, accelerating the development of disease-resistant rice varieties [73–87]. Additionally, the use of drones for targeted spraying helps reduce the volumes of pesticides applied and minimize environmental impact. Altogether, the integration of these biological and technological innovations contributes to building more resilient, sustainable, and economically viable rice production systems [88].

9. Limitations Potential Resistances and Perspectives

Tricyclazole's effectiveness as a fungicide has been well established, but there are instances of resistance to this fungicide in some areas, particularly Japan. Resistance has primarily occurred due to genetic mutations in *Magnaporthe oryzae* that modify the melanin biosynthesis route, and hence, render the pathogen less sensitive or completely insensitive to tricyclazole inhibition. This resistance constitutes a significant threat to the sustainable use of tricyclazole, thus the implementation of responsible management of biocontrol is necessary. To reduce the risk of the emergence and subsequent spread of resistance, an integrated approach that consists of alternating fungicides with different modes of action is required. Rotating or mixing fungicides with different modes of action will reduce selection pressure on the pathogen. Furthermore, an integrated and alternative management strategy that includes cultivating rice varieties resistant to blast disease, and to some extent employing biocontrol agents provided that they are antagonistic agents, or natural extracts, in conjunction with chemical fungicides will help lessen the impacts of chemicals and improve the overall management of this disease. To this end, new classes of fungicides with new modes of action, along with combined and sustainable methods need to be developed in order to maintain effective levels of rice protection while conserving the health of agricultural production ecosystems.

10. Conclusions

This review outlines the efficacious and consistent activity of tricyclazole as an effective management practice to mitigate rice blast disease (*Pyricularia oryzae*) in a range of local agroecological settings. When applied as a seed treatment, foliar spray, or a combination of both, this fungicide has shown a robust ability to significantly reduce disease severity, slow the advancement of the disease, and following good agronomic practice improve grain yield. Its specific mode of action focused on the inhibition of melanin biosynthesis and the ability to induce the expression of defense-related genes in rice is a useful and flexible weapon in blast management approaches overall. Relying exclusively on tricyclazole to manage the disease is impractical; if resistance develops, it will compromise its functionality and pose a biosecurity risk to managing rice blast in the future. In conjunction with tricyclazole, proper and broad use of fungicides belonging to other classes, alternating active ingredients within a rational rotation approach, and normal adopted cultural practices (such as variety, rotation, appropriate sowing dates, reasonable fertilization, etc.) will not only supplement tricyclazole applications but also increase the overall resilience of our cropping systems by avoiding exclusive reliance on chemical options. In conclusion, while tricyclazole remains a central pillar in the control of rice blast, its long-term effectiveness depends on its intelligent combination with other control methods within an integrated disease management framework. It is this holistic approach based on the synergy of chemical, genetic, and agronomic tools that will safeguard crop health and food security in rice-growing regions threatened by this major disease.

Author Contributions

F.E.A. and Y.H. contributed to the literature review, data extraction, and initial manuscript drafting. Y.M. supervised the study and provided critical revisions. Y.E.M. contributed to methodology and discussion improvements. D.H. supervised the project and approved the final version. All authors reviewed and approved the final manuscript.

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Conflict of Interest

The authors declare no conflicts of interest.

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