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Development of resistance to fungicides in wheat leaf rust, *Puccinia triticina* and control strategies

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Review Article

ABSTRACT

Wheat leaf rust, caused by *Puccinia triticina*, is a major global threat to cereal crops, causing significant yield and quality reductions. Climate change and intensive agriculture are increasing epidemic outbreaks, exposing the vulnerability of current agricultural systems and demanding sustainable protection strategies. While chemical fungicides have been the primary control method, their overuse has led to fungicide resistance and reduced effectiveness. This review summarizes fungicide classifications and mechanisms, analyzes resistance development and spread, and presents regional data on pathogen sensitivity. It emphasizes integrated disease management, including agronomic practices, fungicide rotation, biocontrol agents, and biotechnological solutions to minimize environmental impact and improve agroecosystem resilience.

Keywords: Wheat leaf rust, *Puccinia triticina*, Fungicides, Control strategies.

INTRODUCTION

Wheat leaf rust, *Puccinia triticina* is among the most dangerous and widespread diseases of cereal crops, affecting vast areas of cultivated land across major wheat-growing regions worldwide. According to the Food and Agriculture Organization of the United Nations (FAO), annual yield losses due to leaf rust can reach 15–40%, particularly in regions with mild climates and high humidity (Dhawan & Peshin 2009). The disease occurs widely across Asia, Europe, and the Americas, including countries such as Kazakhstan, India, Ukraine, and Brazil (Bahri *et al.* 2025; Gvozdeva *et al.* 2025). The fungal pathogen poses a major threat to wheat production, potentially reducing yield of susceptible cultivars by up to 50% under epidemic conditions. The continuous emergence and persistence of resistant pathogen strains highlight the urgent need for innovative and sustainable disease management strategies (Abou-Zeid & Mourad 2021). The pathogen penetrates the plant through stomata, forming characteristic brown pustules on leaves, thereby reducing photosynthetic activity, accelerating tissue senescence, and substantially decreasing yield. Of particular concern is the pathogen's high variability: *P. triticina* can undergo recombination and accumulate mutations, allowing it to overcome varietal resistance and adapt to new fungicides (Fig. 1; Gvozdeva & Volkova 2022; Rsaliyev *et al.* 2025).

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Fig. 1. *Puccinia recondita Desm.* (*www.syngenta.kz)*

Fungicides, encompassing both chemical and biological plant protection agents, play a crucial role in limiting the spread of wheat leaf rust and other fungal diseases (Fig. 2). Fig. 2 presents a classification of fungicides according to their functional roles (preventive, curative, and immunizing) and major areas of application, including seed treatment, soil disinfection, protection of dormant plants, and in-season disease control. This classification facilitates the rational selection of fungicides based on crop phenology and phytopathological conditions.

Their classification is based not only on chemical nature but also on principles of cross-resistance, as reflected in the recommendations of the Fungicide Resistance Action Committee (FRAC) in Europe and the North American Fungicide Resistance Action Committee (NAFRAC; Beresford *et al.* 1999). In recent years, particular attention has been given to the development of resistance management strategies, as many fungicide groups are already at risk of reduced effectiveness.

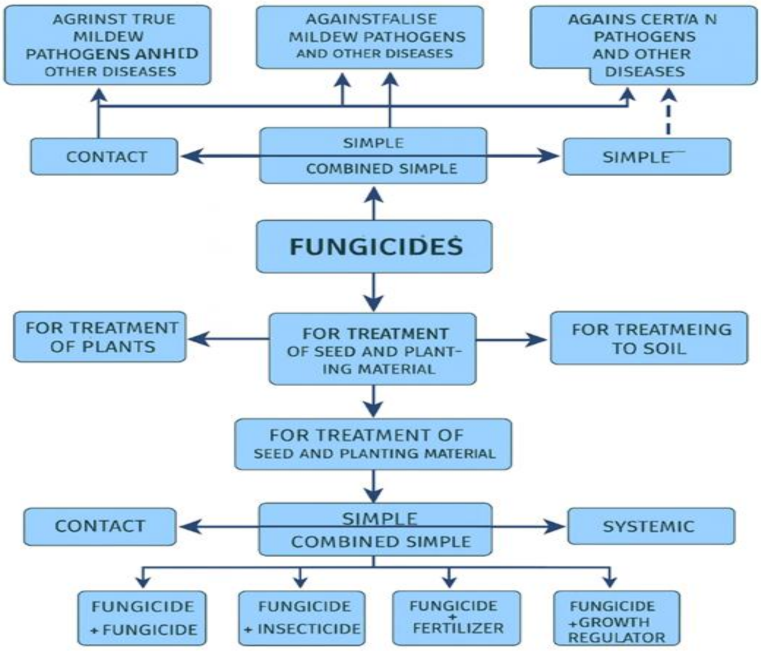

Fig. 2. Classification of fungicides according to their functional groups and application purposes (Gruzdev 1987; Hirooka & Ishii 2013; Gvozdeva & Volkova 2022)

The relevance of this issue is also evident at the regional level. Studies conducted in Belarus and Kazakhstan highlight the necessity of a systematic approach to fungicide application that accounts for the genetic variability of the pathogen and local phytopathological conditions (Hirooka & Ishii 2013; Kruppenko 2023). For instance, in cereal crops, 61 formulations are registered for seed treatment and 100 for in-season disease control. The active ingredients used in the protection of cereals in the region belong to 11 chemical classes: phenylamides, methyl benzimidazole carbamates, aryl-phenyl-ketones, carboxamides (SDHI), strobilurins (QoI), anilinopyrimidines, azonaphthalenes, phenylpyrroles, azoles (DMI), amines (morpholines), and dithiocarbamates. Knowledge of their classification and mechanisms of action allows researchers and practitioners to navigate the diversity of plant protection products and to select fungicides appropriate to the phytopathological situation, the dynamics of disease development, and prevailing hydrothermal conditions (Hirooka & Ishii 2013; Kruppenko 2023).

In particular, Kazakhstani researchers are actively investigating the genetic basis of winter wheat resistance to leaf rust, which makes this research area especially relevant for Central Asia (Rsaliyev *et al.* 2025).

The aim of this review is to systematize current knowledge on the classification and mechanisms of action of fungicides and to analyze strategies for their use in preventing the development of resistance in wheat leaf rust pathogens.

Classification of fungicides and their effects on plant pathogens

Based on their mode of action, fungicides are classified into three main categories:

- Preventive (protective) – applied before infection to prevent pathogen establishment.
- Curative (eradicant or therapeutic) – used shortly after infection to stop pathogen development.
- Immunizing – induce plant defense mechanisms to enhance resistance.

Depending on the purpose of application, fungicides are further classified into the following groups:

1. Seed treatment fungicides: used to disinfect seed material, particularly for cereals, industrial, and annual crops. Early seed treatment with combined formulations can significantly reduce the number of treatments required during the growing season.
2. Fungicides for greenhouse soil disinfection: applied to protect crops grown from seedlings. These agents are highly volatile and act as vapors or gases.
3. Fungicides for dormant perennials: used to eliminate pathogens surviving in overwintering plant tissues, such as in fruit trees and grapevines.
4. Fungicides applied during the growing season: intended for disease control during the active growth and development of crops.

According to their distribution within plants, fungicides are classified as contact or systemic (Fig. 3). Contact fungicides remain on the plant surface and provide external protection, whereas systemic fungicides are absorbed and translocated within plant tissues, ensuring internal suppression of pathogen development. The persistence and efficacy of contact fungicides largely depend on environmental factors such as wind and precipitation.

Systemic fungicides, on the other hand, are absorbed by the plant and circulate internally. Their effectiveness and persistence are primarily determined by the nature and rate of the plant's metabolic processes.

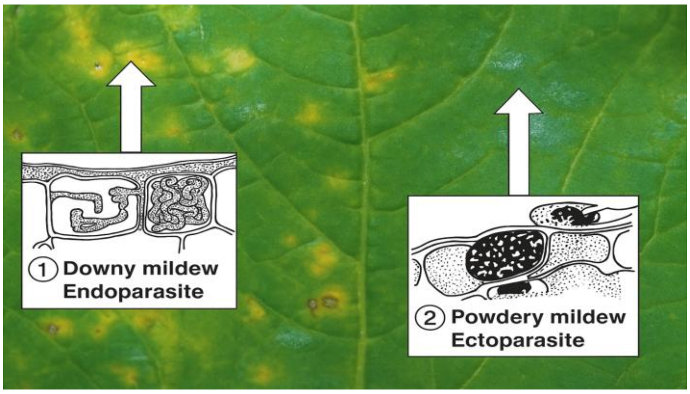

Fig. 3. Sites of action of systemic and contact fungicides (Source: Gruzdev1987; Beresford *et al.* 1999; Hirooka & Ishii 2013; Kolmer 2013).

The mechanisms of fungicidal action are highly diverse. For chemically derived fungicides, the following effects are characteristic:

- disruption of respiratory processes (strobilurins);

- inhibition of nuclear division in fungal cells (systemic fungicides such as thiophanate-methyl and benzimidazoles);
- stimulation of metabolic compounds in plants that act as antifungal phytoalexins or antibiotics (aluminum phosphite);
- localized lignification and necrosis formation, which serve as barriers to pathogen penetration into healthy host tissues (a phenomenon known as the hypersensitive reaction);
- inhibition of pathogen toxins necessary for development within the host plant, thereby increasing host resistance to infection (fungicides with such activity are often referred to as elicitors);
- blockage of ergosterol biosynthesis in fungal cell membranes (derivatives of morpholines, pyrimidines, and triazoles);
- inhibition of nucleic acid synthesis (phenylamides);
- suppression of energy metabolism (oxathiin derivatives).

Some fungicides combine multiple mechanisms of action. For example, arachidonic acid induces a hypersensitive reaction while simultaneously stimulating the production of phytoalexins.

For biologically derived fungicides, the mechanisms include:

- penetration into plant tissues and induction of systemic resistance, resulting in the production of compounds that prevent infection by virulent pathogen strains;
- competition with pathogenic strains for host colonization (for example, *Rhizoctonia solani* strains with reduced virulence applied for the protection of various crops);
- hyperparasitism, involving penetration into the host after pathogen infection, secretion of toxins that kill the pathogens, and utilization of their degraded products as nutrients (Brent & Hollomon 1995; Leadbeater 2012; Hirooka & Ishii 2013; Lucas *et al.* 2015; Köhl *et al.* 2019).

Fungal and bacterial diseases are characterized by diverse pathways of pathogen entry into plants (Fig. 3). Upon reaching the plant surface, pathogens may penetrate through hydathodes, stomata, or nectaries, or directly through intact epidermal tissues, as observed in some ascomycete fungi causing powdery mildew. In addition, pathogen development strategies differ, with some species growing externally as ectoparasites and others developing internally as endoparasites within host tissues. Therefore, effective chemical disease control must be as adaptive as the pathogens themselves (Hirooka & Ishii 2013; Sinegovsky 2024).

Risks of resistance development to different classes of fungicides

Resistance to fungicides poses a serious threat to effective disease control. It is widespread among many phytopathogenic fungi across the world, and many newly developed fungicides are at high risk of selecting for resistant fungal populations. Although strategies to prevent or delay resistance have been proposed, the diversity of trade names complicates their correct implementation by growers. This review summarizes current resistance management strategies for various fungicide groups and provides a reference table to help producers identify fungicide classes (Pscheidt 2015).

Fungicide resistance has become a major global issue in modern agriculture. Field resistance has been reported for nearly 200 crop–pathogen combinations and in approximately half of all known fungicide groups. Many additional cases of resistance are suspected but remain undocumented. Although the resistance risk for many fungicides may not be as high as for benomyl, specific management strategies have been developed and implemented to prevent control failures and preserve the effectiveness of new products (Damicone & Smith 2009).

The development of fungicide resistance in phytopathogenic fungi is a complex and multifactorial process driven by repeated fungicide applications and strong selection pressure. Continuous exposure to fungicides with site-specific modes of action promotes the accumulation of mutations in target genes, leading to the gradual dominance of resistant pathogen genotypes within populations. As a consequence, the efficacy of several major site-specific fungicide groups -such as benzimidazoles, phenylamides, demethylation inhibitors (DMIs), quinone outside inhibitors (QoIs), and succinate dehydrogenase inhibitors (SDHIs) - has been significantly reduced. Recent studies have provided deeper insights into the emergence, spread, behavioral traits, diagnostic approaches, and molecular mechanisms of resistance across different fungicide classes and pathogen species (Thind 2022).

The chemical method remains one of the most effective approaches for protecting economically important agricultural crops and ensuring yield quality. Currently, at least 150 fungicidal compounds with different modes of action are used in global agriculture, and the number of registered products based on them is several times higher. Triazoles and strobilurins are among those fungicides whose introduction in the 1980s–1990s represented a breakthrough in control of the most harmful pathogens (Fernández-Ortuño *et al.* 2008). However, reliable protection of plants from fungi and oomycetes often requires multiple fungicide applications repeated each growing season, which worsens environmental pollution and increases the risk of resistance development in these phytopathogens.

Resistance evolution is therefore one of the most challenging consequences of fungicide use, rendering treatments in many cases ineffective and economically unjustifiable (Brent & Hollomon 1995; Oliver *et al.* 2014; Lucas *et al.* 2015). Attempts to manage resistant forms of phytopathogenic fungi and oomycetes by increasing fungicide doses and treatment frequency are usually counterproductive, as they promote the spread of increasingly resistant pathogen populations.

The dominant trends in modern agriculture aimed at ensuring environmental sustainability include reducing fungicide dosages without compromising protective efficacy and overcoming pathogen resistance. At the same time, abandoning modern fungicides belonging to high- and medium-resistance risk groups, such as strobilurins and triazoles, is impractical, as they provide highly effective control of a wide range of diseases and offer several additional agronomic benefits (Fisher *et al.* 2018; Kolmer 2019; Shcherbakova 2019).

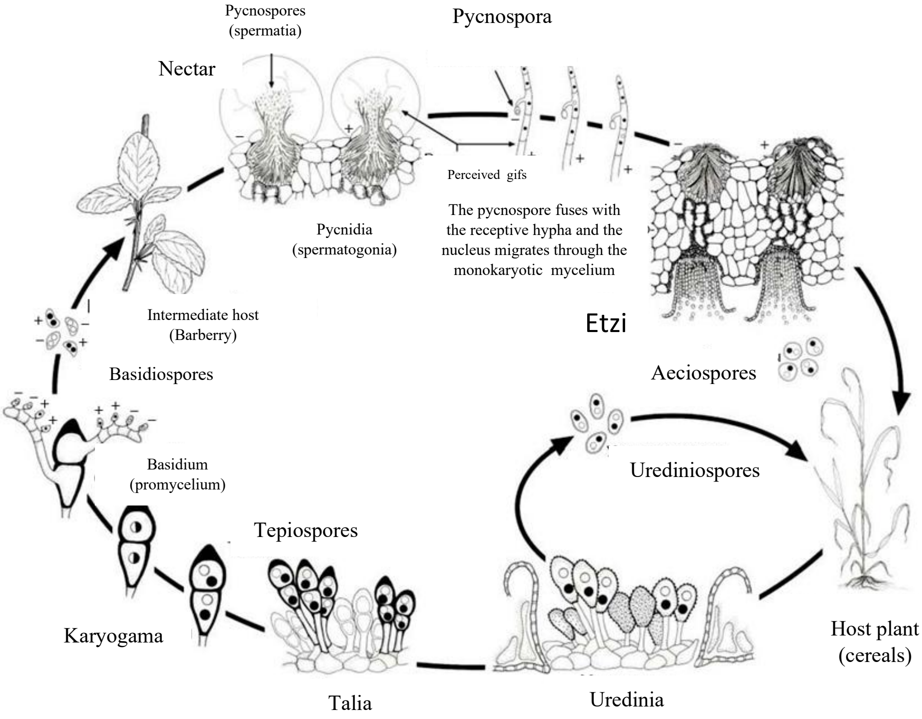

Fig. 4. Life cycle of a heteroecious, macrocyclic cereal rust. The alternate host for stem rust-Puccinia graminis is Berberis vulgaris (barberry); for leaf rust-*Puccinia triticina*, *Thalictrum speciosissimum* (meadow rue); for crown rust-*Puccinia coronata*, *Rhamnus cathartica* (buckthorn): (Kolmer 2013).

Rust pathogens cause significant damage to cereal crops, with yield losses reaching 50% or more under favorable conditions (Roelfs 1974). In winter wheat, three rust fungi are known to occur. The causal agent of wheat leaf (brown) rust is *Puccinia triticina* Eriks., a heteroecious and highly specialized obligate parasite with a complex life cycle. The fungus has more than 200 physiological races that differ in virulence (Gultyaeva *et al.* 2018).

Sources of infection include infected winter cereal seedlings, volunteer plants, alternate hosts such as *Thalictrum* and *Isopyrum*, as well as grass weeds (Salina *et al.* 2015). Pathogen development is favored by warm and humid weather, with optimal temperatures ranging from 20 to 25 °C and the presence of free moisture (Anpilogova & Volkova 2000; Sokolova *et al.* 2020). During the growing season, infection occurs via urediniospores dispersed by wind currents over distances of up to 1000 km (Sinegovsky 2024).

The sensitivity of rust pathogens to modern fungicides has been evaluated in several regional studies. The sensitivity of the North Caucasian population of the barley leaf rust pathogen (*Puccinia hordei* G.H. Otth) to triazole- and strobilurin-based fungicides was evaluated using the following formulations: Amistar Gold, SC (azoxystrobin, 125 g L^{-1} + difenoconazole, 125 g L^{-1}); Amistar Extra, SC (azoxystrobin, 200 g L^{-1} + cyproconazole, 80 g L^{-1}); Baley, EC (azoxystrobin, 120 g L^{-1} + propiconazole, 180 g L^{-1}); and Delaro, SC (prothioconazole, 175 g L^{-1} + trifloxystrobin, 150 g L^{-1}). The study was carried out under controlled greenhouse conditions at the Federal State Scientific Research Center using winter barley of the susceptible cultivar 'Vivat' developed at the Donskoy Agricultural Research Center. Seedling-stage plants were inoculated with the North Caucasian population of *P. hordei*. Fungicide treatments were applied at the onset of first disease symptoms at rates of 0 (control, untreated), 50, 100, 150, and 200% of the recommended dose.

It was found that treatment of infected barley plants with Baley, EC at different rates resulted in biological efficacy ranging from 87.3 to 100%; Delaro, SC — from 78.1 to 100%; Amistar Extra, SC — from 79.2 to 100%; and Amistar Gold, SC — from 85.3 to 100%. The use of the recommended dose (100%) reduced disease development by more than 96.9% in all variants. At higher fungicide rates (150 and 200%), biological efficacy reached 100%. The high sensitivity of the North Caucasian *P. hordei* population to the active ingredients of the tested fungicides was confirmed. For all fungicides tested, LC_{50} and LC_{95} values were significantly lower than the recommended working concentration. This result can be attributed to the presence of active ingredients from different chemical classes with distinct mechanisms of action, ensuring high effectiveness in suppressing barley leaf rust and reducing the risk of resistance development (Gvozdeva *et al.* 2024).

Under epidemic conditions of wheat leaf rust on moderately and highly susceptible modern cultivars, grain yield losses can reach 30% (Figueroa *et al.* 2018). A high incidence of the pathogen has been reported in many grain-producing countries, including Argentina (Germán *et al.* 2007), Brazil (Germán *et al.* 2007), Canada (McCallum *et al.* 2021), Germany (Bolton *et al.* 2008), Latvia (Peksa & Bankina 2019), and China (Zhang *et al.* 2020).

In the Russian Federation, in recent years, the pathogen has been detected on more than 500 thousand hectares of winter crops. The most favorable regions for its development are the Volga, North Caucasus, and Southern Federal Districts. In 2020, disease prevalence reached up to 100% in the Sernursky District of the Republic of Mari El and the Dyurtyuli District of the Republic of Bashkortostan. In the Southern Federal District, 39 thousand hectares of winter cereals were treated against the disease. The highest prevalence was recorded in the Dinskoy District, where it reached 32% over an area of 30 hectares (Komarov & Komarova 2022; Ji *et al.* 2023).

In China, wheat leaf rust is primarily controlled using the demethylation inhibitor (DMI) fungicide triadimefon. Although high levels of pathogen resistance to fungicides have been reported, no cases of wheat leaf rust insensitivity to DMI fungicides have been documented in China. The present study assessed the risk of *Puccinia triticina* (Pt) developing resistance to triadimefon. The sensitivity of 197 Pt isolates collected from across the country to triadimefon was determined, and the distribution of EC_{50} values (the concentration at which mycelial growth is inhibited by 50%) showed a continuous multimodal curve, attributed to the extensive use of this fungicide in wheat production. The mean EC_{50} value was 0.46 µg mL^{-1}.

Most tested Pt isolates were sensitive to triadimefon, while 10.2% exhibited varying degrees of resistance. Characterization of parasitic fitness indicated that triadimefon-resistant isolates demonstrated strong adaptive traits in urediniospore germination rate, latent period, sporulation intensity, and lesion expansion rate. No cross-resistance was observed between triadimefon and tebuconazole or hexaconazole, which share a similar mode of action, nor with pyraclostrobin and fluindapyr, which act through different biochemical pathways. Overexpression of the target gene *Cyp51* was shown to confer triadimefon resistance in Pt.

The risk of resistance development to triadimefon in *P. triticina* (Pt) may therefore be considered low to moderate. This study provides important data for fungicide resistance risk management against wheat leaf rust (Gvozdeva &Volkova 2022).

Climate change and associated extreme weather conditions contribute to the airborne transmission of new pathogen variants (Nazarov *et al.* 2020). In recent years, scientific advances have made significant contributions to the study of pathogen biology, genomics and evolution, host–pathogen interactions, epidemiology, and disease management (Ul Haq & Ijaz 2020). The most commonly used method for controlling cereal pathogens remains fungicide-based protection. However, it has been observed that certain species develop resistance to the active ingredients in plant protection products (Fisher *et al.* 2018).

The use of chemical crop protection is also associated with environmental contamination, caused by the accumulation of active ingredient residues in soil and grain (Spence *et al.* 2020). Therefore, alternative biological methods of controlling fungal pathogens are being actively explored. Studies have shown that some bacterial strains can be as effective in reducing fungal diseases as the active ingredients in fungicides. Research by Wachowsky *et al.* (2020) demonstrated that bacteria of the genus *Sphingomonas* suppressed the growth of *Fusarium* species as effectively as a triazole fungicide.

Grain yield and quality depend on the cropping system, varietal characteristics, and a number of adverse factors. The greatest threat is posed by fungal diseases, which reduce yields by 15–20%, and in some cases by up to 60%. Their development is determined by weather conditions, crop rotation, preceding crops, soil treatment, and fertilization practices. These infections restrict plant growth and deteriorate grain quality (Wachowska *et al.* 2020).

Cases of insensitivity of *P. hordei* isolates to triazole fungicides have also been reported. All tested isolates of this lineage, including the original isolate from 2001, were insensitive to tebuconazole at application rates six times higher than the recommended maximum field rate of 290 mL ha^{-1}. Further testing revealed insensitivity in several other *P. hordei* pathotypes that were not members of the "insensitive" lineage. It is likely that these pathotypes originated from the alternate host *Ornithogalum* in South Australia and were derived from isolates of the "insensitive" lineage that had recombined with other local sensitive isolates (Różewicz *et al.* 2021).

Strategies for managing fungicide resistance

Effective management of fungicide resistance requires an integrated approach combining chemical, agronomic, and biological measures. Wheat leaf rust, *Puccinia triticina*, is one of the most destructive diseases of cereal crops, causing considerable yield losses. The application of fungicides remains the principal strategy for disease management; however, the frequent and repetitive use of products from the same chemical class has led to the emergence of resistant pathogen populations. We provide a comprehensive review of current approaches to wheat leaf rust control and strategies for managing fungicide resistance. The methods discussed include integrated disease management, rotation of fungicides with different modes of action, the use of biological control agents, deployment of resistant cultivars, and the implementation of innovative biotechnological and nanotechnological approaches aimed at enhancing fungicide performance and reducing environmental impact.

Modern crop production faces a rapidly growing challenge of pathogen resistance to fungicides, which is particularly critical for the wheat leaf rust pathogen *Puccinia triticina*. In response to this problem, a number of strategies have been developed to slow down or mitigate the development of resistance.

Integrated plant protection methods

The Integrated Pest Management (IPM) system combines agronomic, biological, and chemical approaches. It reduces pesticide pressure, slows the evolution of resistance, and enhances the ecological sustainability of agroecosystems. For example, crop rotation, the use of resistant cultivars, and timely fungicide applications at the optimal stages of disease development allow effective control of wheat leaf rust with minimal yield losses. According to Franco, IPM represents a sustainable plant protection strategy that integrates all available methods of pest and disease control — agronomic, biological, genetic, and chemical - while minimizing risks to the environment and human health (Franco 2020; Ellwood *et al.* 2024).

In the North Caucasus, IPM is particularly relevant, as *Puccinia triticina* populations exhibit high variability in virulence, making traditional protection methods less effective. Studies by Kolbin and Volkova (Morgounov *et al.* 2015) demonstrated that systematic use of combined fungicides such as Rex Duo (containing active ingredients from different chemical classes) exerts directed evolutionary pressure on *P. triticina* populations. As a result, shifts in the frequency of virulent genotypes were observed, with a reduced proportion of races capable of overcoming resistance in specific wheat cultivars. This selective impact contributes to lowering the adaptive potential of the pathogen and limits its diversity. In addition, a general decline in crop infection levels was recorded, expressed as a reduced number of *Uredinia* on leaves and slower epidemic development. These findings indicate that the application of such fungicides not only suppresses disease progression but also influences the microstructural composition of the pathogen population, preventing the dominance of the most aggressive forms (Ellwood *et al.* 2024).

Furthermore, a later study (Gvozdeva & Volkova 2022) investigated the effect of another combined fungicide, Abacus Ultra, SC. Its application resulted in reduced sporulation intensity, an extended latent period, and decreased aggressiveness of *P. triticina* populations.

Fungicide rotation

Fungicide rotation involving agents with different modes of action represents a key component of resistance management strategies. Numerous studies have demonstrated that resistance develops more rapidly when fungicides from a single chemical class are repeatedly applied, particularly in the case of quinone outside inhibitor (QoI) fungicides (strobilurins), which exert strong selection pressure and contribute to the emergence of resistant pathogen populations, including those responsible for wheat leaf rust (Hawkins 2024).

The implementation of planning systems based on the FRAC (Fungicide Resistance Action Committee) classification is a crucial strategy for managing pathogen resistance. FRAC is an international organization that brings together plant protection experts and classifies fungicides according to their modes of action. Each chemical class is assigned a unique code (for example, QoI – group 11; DMI – group 3), enabling agronomists and growers to design effective fungicide rotation and mixture schemes.

According to FRAC recommendations, prolonged use of fungicides with the same mode of action increases the risk of selecting resistant pathogen forms. For instance, repeated applications of QoI fungicides (strobilurins) often lead to rapid resistance development caused by a single mutation in the mitochondrial *cytochrome b* gene. To prevent this, it is recommended to rotate fungicides from different FRAC groups and to use combination products containing active ingredients with distinct modes of action.

Moreover, the adoption of FRAC-based planning systems allows optimization of treatment schedules throughout the growing season, reduction of application frequency without loss of efficacy, integration of chemical measures with biological and agronomic practices, and prevention of multiple resistance (simultaneous resistance to several fungicides).

In the United Kingdom, Germany, and other EU countries, such rotation schemes have been developed and adapted at the national level through the initiatives of FRAG (Fungicide Resistance Action Group), including FRAG-UK. These initiatives provide farmers and agronomists with recommendations for the sustainable use of specific active ingredients, depending on the target pathogen and the field's treatment history. The effectiveness of these approaches has been scientifically validated and confirmed through both experimental and field studies (Franco 2020).

For example, in experiments on wheat leaf rust, optimal results were achieved through the rotation of triazoles and strobilurins. The use of combination products containing both groups, such as Abacus Ultra (epoxiconazole + pyraclostrobin), demonstrated high efficacy and helped prevent the emergence of resistant pathogen populations due to its dual mode of action (Gvozdeva & Volkova 2022; Gvozdeva *et al.* 2025). *In vitro* experiments have also confirmed that inhibition of urediniospore germination can be effectively achieved with triazoles and strobilurins, particularly when they are applied in combination (Hawkins 2024).

Field and laboratory studies have confirmed that appropriate fungicide rotation enhances biological efficacy and maintains high pathogen sensitivity, as evidenced by EC_{50} and EC_{95} values close to recommended application rates (Meena *et al.* 2021; Vasilchenko *et al.* 2023).

Biological control

Biological control represents an important complementary strategy within integrated disease management systems. The use of antagonistic microorganisms such as *Trichoderma* spp. and *Bacillus* spp. has been shown to be effective against *Puccinia triticina*. These beneficial organisms not only suppress the development of the pathogen but also induce plant defense mechanisms, thereby enhancing resistance to subsequent infections (Vasilchenko *et al.* 2023). These mechanisms contribute to a reduced fungicide load and enhance the sustainability of crop protection systems.

Microorganisms of the genus *Trichoderma* demonstrate multifactorial antagonistic activity against fungal pathogens, including rust-causing fungi such as *P. triticina*. Their main mode of action involves the production of hydrolytic enzymes-particularly glucanases, chitinases, and proteases-that disrupt the structural integrity of pathogen cell walls and proteins.

These enzymes are actively secreted upon contact between *Trichoderma* and the pathogen's mycelium, resulting in degradation of the pathogen's cell wall, disruption of osmotic stability, and ultimately cell death. This process, known as mycoparasitism, represents a form of antagonism in which one fungus parasitizes another.

In addition to its antagonistic activity, *Trichoderma* functions as a plant growth-promoting agent. It contributes to the activation of induced systemic resistance (ISR), stimulates the synthesis of phytoalexins and other defensive metabolites, enhances the uptake of macro- and micronutrients - particularly phosphorus and iron - and increases the activity of antioxidant systems.

Some strains of *T. harzianum* and *T. viride* also synthesize secondary metabolites with fungicidal activity, further enhancing their overall efficacy. The integration of these strains into crop protection programs contributes to a reduction in chemical treatments, decreases the toxicity of agricultural practices, and increases plant tolerance to environmental stress factors. Therefore, *Trichoderma* fulfills a dual role - as a biofungicide and a plant growth biostimulant - making it a crucial component of biological control strategies against rust diseases (Franco 2020).

Biological formulations also help reduce the chemical load and minimize the risk of resistance development. When incorporated into an integrated plant protection system, biological control enables a decrease in the frequency of chemical fungicide applications and prolongs their effectiveness (Köhl *et al.* 2019; Kolmer 2019).

CONCLUSION

Thus, effective management of wheat leaf rust requires a comprehensive approach that integrates agronomic practices, rational use of chemical fungicides, biological control, deployment of resistant cultivars, and the application of modern biotechnologies. Importantly, fungicide resistance should be regarded not only as a phytopathological problem but also as an agroecosystem-level challenge driven by long-term selection pressure and environmental constraints. The implementation of integrated protection systems, rotation of active ingredients from different chemical classes, and the use of biocontrol agents, along with innovative solutions such as nanotechnologies and genome editing, can significantly slow the development of pathogen resistance while reducing environmental impact and maintaining crop productivity.

Future research should therefore focus on strengthening the sustainability of agroecosystems through the development of durable resistant cultivars, identification of novel biological control agents, and optimization of fungicide application schemes based on continuous monitoring of pathogen populations and resistance dynamics.

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