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Why are fungicides losing their power? Understanding fungicide resistance in plant pathogens

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Abstract

Fungicide resistance in plant pathogenic fungi has emerged as a major challenge to sustainable crop protection. This threatens the effectiveness of chemical disease management. Intensive, repeated application of fungicides, mainly those with single-site modes of action, imposes selection pressure. This favours the multiplication and survival of resistant pathogen strains. Resistance develops through several mechanisms, such as target-site mutations, overexpression or duplication of target genes, metabolic adaptation, enhanced efflux activity and epigenetic regulation. These mechanisms reported in several economically important pathogens, like *Botrytis cinerea*, *Fusarium graminearum*, *Puccinia striiformis* and *Plasmopara viticola*. Understanding the molecular basis and evolutionary dynamics of this resistance is essential for developing effective management strategies. Rotating fungicides with different modes of action, limiting repeated applications, combining multi-site and single-site fungicides and integrating biological and cultural control practices help delay resistance development. Ultimately, sustainable fungicide use, supported by molecular diagnostics and emerging technologies, is crucial for retaining fungicide efficacy and ensuring long-term crop protection.

Keywords: Fungicide resistance, Plant pathogenic fungi, Resistance mechanisms, Target-site mutations, Management

Introduction

Fungal diseases are one of the major causes of crop losses (10-23%) worldwide, affecting the yield and quality of many food crops. Studies indicate that plant pests and pathogens cause global yield losses of approximately 21.5% in wheat, 30% in rice, 22.5% in maize, 17.2% in potato and 21.4% in soybean (Savary *et al.*, 2019). In severe cases, fungal epidemics have even contributed to major food crises such as the Great Irish Famine and the Bengal famine. Beyond yield reduction, fungal pathogens can also compromise food safety. Certain fungi, such as *Aspergillus flavus* and *Fusarium verticillioides*, produce harmful mycotoxins that contaminate food and feed, posing risks to human and animal health (Chen *et al.,* 2019).

Farmers adopt several strategies to manage plant diseases, including cultural practices, resistant varieties and biological control. While these approaches are considered environmentally safer, they often provide limited or inconsistent protection, particularly under conditions of high disease pressure. In comparison, fungicides offer quick, effective and predictable control of many fungal pathogens. Although the prolonged use of fungicides is associated with certain drawbacks, such as environmental concerns, effects on non-target organisms and the risk of resistance development, farmers still rely on them to safeguard crop yield and quality. The potential economic losses caused by severe fungal outbreaks often outweigh these concerns, making fungicides an indispensable component of modern crop protection. Yet, the repeated use of fungicides with similar modes of action has led to the development of fungicide resistance in many pathogenic fungi, reducing their effectiveness and posing a challenge for sustainable crop protection.

What is Fungicide Resistance?

Fungicide resistance is the heritable reduction in the sensitivity of a fungus to a fungicide (Delp and Dekker, 1985). In resistant populations, fungal pathogens can survive and grow even in

the presence of fungicide concentrations that would normally inhibit them. Repeated use of the same fungicide creates selection pressure, where sensitive strains are eliminated while resistant individuals survive and multiply. Over time, these resistant strains dominate the pathogen population, reducing the effectiveness of fungicides under field conditions. Therefore, fungicide resistance can be viewed as an evolutionary response of pathogens to continuous fungicide exposure.

Why Does Fungicide Resistance Occur?

The development of fungicide resistance is closely related to the mode of action of fungicides. Copper and sulphur which are the older fungicides, are multi-site inhibitors, where they inhibit several biochemical processes in fungal cells, thus making the fungi difficult for resistance development, whereas the modern fungicides are usually single-site inhibitors that target specific enzymes or metabolic pathways. Development of mutation can help to prevent the binding of fungicides to the target gene, thereby allowing the pathogen to survive. Since 1970s, the shift toward the single-site inhibitors has shown to improve disease control, but it also has created the risk of resistance development (Brent and Holloman, 1995).

Repeated application of fungicides has enhanced the survival and the multiplication of the resistant pathogen strains. Therefore, fungicide resistance has emerged globally in various plant pathogens that impact major crops. A few key examples are listed in Table 1. The development of fungicide resistance is closely related to the mode of action of fungicides.

Table 1. Examples of Fungicide Resistance in Important Plant Pathogens

Pathogen	Crop affected	Fungicide group	Reference
Botrytis cinerea	Grapes, vegetables	QoI fungicides	Hahn, 2014
Fusarium graminearum	Wheat and other cereals	DMI fungicides	Jayawardana and Fernando, 2024
Puccinia striiformis f. sp. *tritici*	Wheat	SDHI and DMI fungicides	Cook *et al.*, 2021
Plasmopara viticola	Grapes	Phenylamide fungicides	Massi *et al.*, 2021
Powdery mildew fungi	Cucurbits, grapes	DMI fungicides	Vielba-Fernandez *et al.*, 2020

The examples above illustrate the widespread occurrence of fungicide resistance in several important plant pathogens affecting major crops. These resistance cases arise through specific biological and molecular mechanisms that enable pathogens to survive fungicide exposure. Some of the major mechanisms responsible for fungicide resistance in plant pathogenic fungi are summarised in Table 2.

Table 2. Mechanisms of Fungicide Resistance in Plant Pathogenic Fungi

Fungicide group	Target protein /gene	Major resistance mechanism	Example pathogen(s)	Reference
Benzimidazoles	β-tubulin	Point mutations in β-tubulin gene (codons 167, 198, 200) altering fungicide binding	*Botrytis cinerea*, *Fusarium graminearum*, *Corynespora cassiicola*	Davidse, 1986; Ma & Michailides, 2005
Myosin inhibitors (Phenamacril)	Myosin I (MyoI)	Mutations in MyoI affecting ATPase activity	*Fusarium graminearum*, *Fusarium fujikuroi*	Zheng *et al.*, 2015; Fu *et al.*, 2020
Sterol demethylation inhibitors (DMIs)	Cyp51 (14-α-demethylase)	Target mutations, gene overexpression, gene duplication, efflux pump activity	*Zymoseptoria tritici*, *Fusarium graminearum*, *Venturia* spp.	Brent & Hollomon, 1995; Sánchez-Torres, 2021
QoI fungicides (Strobilurins)	Cytochrome b	Mutations such as G143A, F129L, N256S in cytb	*Botrytis cinerea*, *Colletotrichum gloeosporioides*, *Plasmopara viticola*	Bartlett *et al.*, 2002; Sierotzki *et al.*, 2007
SDHI fungicides	SdhB, SdhC, SdhD	Mutations in Sdh genes affecting mitochondrial respiration	*Botrytis cinerea*, *Fusarium graminearum*	Leroux *et al.*, 2010; Shi *et al.*, 2021
Anilinopyrimidines	Methionine biosynthesis enzymes	Metabolic changes and mitochondrial mutations	*Botrytis cinerea*, *Penicillium digitatum*, *Sclerotinia sclerotiorum*	Mosbach *et al.*, 2017; Hou *et al.*, 2018
Carboxylic acid amides (CAA)	Cellulose synthase (CesA3)	Mutations in CesA3 gene	*Plasmopara viticola*, *Pseudoperonospora cubensis*	Blum *et al.*, 2010; Gisi & Sierotzki, 2015
OSBPI fungicides	Oxysterol-binding	Mutations in Orp1 gene	*Phytophthora capsici*, *Phytophtho*	Miao *et al.*, 2016;

	protein (Orp1)		*ra infestans*	Li *et al.*, 2022
Multidrug resistance	Efflux transporter genes	Overexpression of efflux pumps	*Botrytis cinerea*, *Penicillium digitatum*	Hahn, 2014; Leroch *et al.*, 2013
Epigenetic resistance	RNAi pathways	Regulation of gene expression without DNA mutation	*Mucor circinelloides*, *Candida albicans*	Calo *et al.*, 2014; Patra *et al.*, 2022

Mechanisms of Fungicide Resistance in Plant Pathogens

Plant pathogenic fungi develop resistance to fungicides by various molecular and physiological mechanisms; this reduces their sensitivity toward fungicides (Table 2). The mechanisms include the alteration of the target site, changes in target gene expression, the metabolic adaptation and the detoxification process. Fungi also develop resistance through lateral modification of the target site and changes in the shape of the protein, which prevent the fungicides from binding. The altering genes include *β-tubulin*, *cytochrome b*, *Cyp51* and *succinate dehydrogenase* subunits; thus, the alteration provides resistance to fungicides such as benzimidazole, Quinone Outside Inhibitors (QoI), Demethylation Inhibitors (DMI) and Succinate Dehydrogenase Inhibitors (SDHIs) (Davidse, 1986; Bartlett *et al.*, 2002; Leroux *et al.*, 2010; Sánchez-Torres, 2021). Another common mechanism is the modification of the gene expression by the pathogens through the overexpression or duplication of the target genes. The increase in expression of the *Cyp51* gene decreases the sensitivity to DMI fungicides in many fungal species (Brent & Hollomon, 1995). Some of the pathogens develop resistance through alteration of metabolic or mitochondrial pathways, where the alteration makes the pathogens able to survive myosin inhibitors and anilinopyrimidine treatments (Zheng *et al.*, 2015; Mosbach *et al.*, 2017). Pathogens like *Botrytis cinerea* and *Penicillium digitatum* show multidrug resistance (MDR) by overexpression of the efflux transporter proteins, where the fungicide is pumped out of the cell, thereby lowering the intracellular concentrations of the fungicides (Hahn, 2014; Leroch *et al.*, 2013). In some recent studies, epigenetic regulation plays an important role in telling how the fungi are able to survive. Studies mention that RNA interference and chromatin modifications by the pathogens help to withstand the fungicides temporarily without the need for permanent DNA mutation (Calo *et al.*, 2014; Patra *et al.*, 2022). The overall understanding of the concept of these resistance mechanisms is important for effective fungicide resistance management in crop protection.

Management of Fungicide Resistance

In integrated disease management, fungicides are an important component, but their intensive use of their site-specific target has led to the rapid emergence of resistant pathogens in the cropping systems (Ma & Michailides, 2005). For this, effective resistance management is required for enhancing the fungicide efficacy and maintaining the sustainable disease control approach. The Fungicide Resistance Action Committee has recommended guidelines in need of rotating fungicides with different modes of action (e.g., QoI, DMI and SDHI) to prevent the pathogen populations from developing cross-resistance (Brent & Hollomon, 1995). Apart from this, the restriction on the applications of high-risk fungicides within the cropping season helps to avoid the repeated curative treatments, which further delays disease development (Corkley *et al.*, 2022). The encouraged use of a mixture of the single-site fungicides along with multi-site protectants can reduce the developing of the resistant strain pathogen populations. The management by integration of the chemical control along with non-chemical control by utilizing the resistant cultivars, crop sanitation, cultural practices and biological control significantly reduces the pathogen populations and slows down the resistance evolution. The emerging disease control approaches such as RNA interference (RNAi) are also explored as innovative tools to complement conventional fungicides, thus preventing the resistance risks developing by the pathogens as well as for future crop protection systems (Cagliari *et al.*, 2019).

Future Perspectives

The advancement in molecular biology and genomics improves the detection and monitoring of pathogen populations resistant to fungicides. And the emerging technologies such as RNA interference (RNAi) also hold promising approaches for the specific control of fungal pathogens (Cagliari *et al.*, 2019). Along with this, the development of fungicides with novel modes of action and the integration of the precision agriculture tools can optimize the fungicide usage and thus reduce the resistance risk of the pathogen populations.

Conclusion

Fungicide resistance is regarded as a major

challenge for a sustainable way of plant disease management. Adopting integrated disease management, which includes proper usage of fungicides, monitoring along with an alternative control approach, which is essential in reducing the risk of resistance. The cooperation among the researchers, framers and industry will be necessary for maintaining the effectiveness of fungicides and to ensure sustainable agricultural production.

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