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EDITORIAL

A special isssue on fungicide resistance and management strategies

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Fungicides with single site modes of action play a crucial and economically vital role in Integrated Pest Management (IPM) strategies for controlling diseases in modern agriculture. However, their effectiveness is under threat due to the adaptability of plant pathogens. There has been a significant increase in the number of research reports in the past decades on the decline of sensitivity to various active ingredients in laboratory settings and reduced performance in the field.

The failure of a fungicide to combat disease in the field due to the increase and selection of resistant populations has substantial economic and environmental ramifications. It underscores the critical need for responsible chemical stewardship and a comprehensive understanding of all contributing factors for improved resistance management.

Many efforts are underway to understand the emergence, selection, and mechanisms of resistance alongside the integration of resistance monitoring to support sustainable production. The dynamic nature of fungicide resistance is related to factors such as fungicide mode of action (MOA), pathogen biology, climate, and agricultural practices.

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Studies on baseline fungicide sensitivity and efficacy monitoring, as well as reports of target gene modifications and overexpression associated with loss of effectiveness in the field, have intensified in Brazil and elsewhere. Between 1997 and 2007, approximately 120 articles were published on these topics per year. This number rose to 250 between 2009 and 2019, and in the last five years, an average of over 500 articles have been published related to fungicide sensitivity and resistance per year.

There is a need for more MOAs for disease management to alleviate the pressure for resistance selection and increase the effective lifespan of fungicides. However, the development of products with new MOAs is a slow and expensive process, underscoring the fundamental importance of judiciously employing existing active ingredients.

The Fungicide Resistance Action Committee (FRAC) International and FRAC Brazil play a fundamental role in supporting producers and researchers with information on fungicide chemistry, resistance mechanisms, methodologies for studies, and guidance for appropriate management. Information is constantly updated through specific working groups, with collaboration from renowned researchers worldwide.

The need for knowledge in the field of fungicide resistance aimed at establishing better management strategies to extend the productive life of existing fungicides was the driving force behind Tropical Plant Pathology's consideration of a special issue on this topic. Most international events on issues related to plant pathology and plant health include topics related to fungicide resistance. Many public universities and other research institutions have scientists dedicated to projects that address this need, thereby providing agility to the entire crop production sector ensuring better fungicide use, while simultaneously discussing and incorporating new molecules and control methods as alternatives for management.

In this special issue of TPP, we feature three reviews, 10 original articles and short comunications articles covering relevant topics for advancing studies on fungicide resistance for plant disease management. One of the reviews, authored by Dr. Ipsita Samal, a researcher from Sri Sri University in India, summarizes the effect of fungicides on entomopathogenic fungi infection stages, underlying mechanisms, consequences, and opportunities for progress considering resistance to fungicides in entomopathogenic fungi (Samal et al. 2023). Another important review, authored by Dr. Hideo Ishii from the University of Tsukuba, Japan, provides insights into new chemical fungicides in relation to the risk for resistance development. The author reviewed the literature on newly developed fungicides recently registered or potentially coming to market. Additionally, the application of disease resistance inducers, crop resistance breeding, and biological control is briefly discussed (Ishii 2023). A group of Brazilian researchers conducted the third review on fungicide resistance in this special edition and discussed strategies for managing fungicide resistance under the tropical agroecosystem in Brazil (Ceresini et al. 2024). This review examines historical and current scenarios of fungicide resistance to delay the development and selection of resistant variants, and some strategies are recommended to minimize the progression of fungicide resistance.

Articles in this special edition cover studies on baseline sensitivity and mechanisms of resistance to different fungicides in crops such as soybeans, beans, and wheat, as well as perennial crops such as apple, coffee, and persimmon. Three studies address fungicide resistance issues in *Botrytis cinerea* populations from strawberry in Brazil and the United States.

Linhares de Castro et al. (2022) revealed a geographical expansion of *Colletotrichum plurivorum* of soybeans since its initial report. Variability in sensitivity to fungicides among *Colletotrichum* spp. and between fungicide sensitive and resistant populations of the same species highlight the need for precise identification of *Colletotrichum* species. Low sensitivity to azoxystrobin and resistance to thiophanate-methyl were detected in the field, suggesting these fungicides may not effectively control anthracnose in soybeans in Mato Grosso and Goiás States, Brazil. Mello et al. (2023) confirmed *C. plurivorum* as the main species causing anthracnose in soybeans in Brazil. Benzovindiflupyr showed the same intrinsic activity on both *C. plurivorum* and *C. truncatum* species. Isolates of *C. plurivorum* and *C. truncatum* in this study were more sensitive to benzovindiflupyr, protioconazole, and difenoconazole than to fluxapyroxad, inpyrfluxam, and mefentrifluconazole. These results provide important information for anthracnose and anti-resistance management in soybeans using SDHI and DMI fungicides.

The sensitivity of *Sclerotinia sclerotiorum* populations to thiophanate-methyl, fluazinam, and procymidone from different regions in Brazil was investigated in various crops, including soybean, bean, cotton, tomato, sunflower, and others. There was no evidence of resistance to fluazinam or procymidone, but 13 isolates from dry common bean fields were resistant to thiophanate-methyl, all with a mutation at codon 240 (L240F) of the β-tubulin gene. Interestingly, the mycelial growth rate of six thiophanate-methyl-resistant isolates decreased with successive transfers on fungicide-free culture medium, but there was no reversion to a sensitive phenotype (Silva et al. 2024).

In a study by Carraro et al. (2023), isolates of different *Colletotrichum* species from persimmon varied in their sensitivity to the fungicides evaluated, with *C. horii* isolates, in general, being more sensitive to site-specific fungicides than isolates from the three other species, *C. chrysophilum, C. nymphaeae* and *C. melonis*. The authors found that the most effective fungicides for controlling persimmon anthracnose in both immature and mature fruit were difenoconazole and mixed formulations of QoI and DMI.

In another *Colletotrichum* study, Meng et al. (2023) found isolates from apple with reduced sensitivity to fluazinam and tebuconazole in lab assays. Both fungicides offer MOA that are different from the fungicides commonly used for bitter rot control. The authors confirmed reduced sensitivity was stable after cold storage. Interestingly, reduced-sensitive isolates were inhibited when fungicides were applied preventively but were less effectively controlled if used curatively (after infection). This research emphasizes that even though field resistance may still be absent for these products, resistance management practices should be implemented to mitigate resistance selection.

Le et al. (2023) reported the cytochrome b gene sequence of the coffee leaf rust pathogen *Hemileia vastatrix* from Vietnam. Sequencing results showed that Vietnamese isolates did not harbor F129L and G143A mutations in exons 2 and 3 of the CYTB gene. The gene was amplified with only three primer pairs that can be used in future to amplify the gene from live or dried mycelia to detect potential resistance to QoI fungicides in *H. vastatrix*.

Maia et al. (2023a, b) evaluated the sensitivity of *Botrytis cinerea* isolates to pyrimethanil, investigated cross-resistance between pyrimethanil and cyprodinil, and evaluated the efficacy of pyrimethanil in controlling gray mold. EC_{50} values of *B. cinerea* for pyrimethanil ranged from 0.0052 to 94.07 µg/ml with a mean EC_{50} value of 6.53 µg/ml. There was a positive correlation between pyrimethanil and cyprodinil EC_{50} values ($r = 0.83$). Moreover, the efficacy of preventive and curative applications of pyrimethanil, cyprodinil and fludioxonil was evaluated in detached strawberry fruit assays and results showed superior performance of fludioxonil. Pyrimethanil and cyprodinil showed greater efficacy against sensitive isolates when applied preventatively with control efficacy of 84.6 and 87.2%, respectively. Overall, pyrimethanil showed good efficacy in the control of gray mold of strawberry, but the authors stress caution and recommend applying resistance management practices.

Another study on the same organism by Bolognesi et al. (2023) determined the baseline sensitivity of *Botrytis cinerea* isolates collected from Florida strawberry fields prior to registration of pydiflumetofen, characterized Sdh-B and Sdh-C mutations conferring resistance to pydiflumetofen, and determined the frequency of pydiflumetofen resistance of *B. cinerea* isolates collected during four strawberry seasons in Florida. Baseline sensitivity of 70 isolates ranged from 0.020 to 0.365 μg/ml. While the product had been used during the 2019–20, 2020–21, 2021–22, and 2022–23 seasons, 271, 195, 156, and 116 *B. cinerea* isolates were collected from commercial fields and the resistance frequency was 0.4% (one isolate), 8.7% (17 isolates), 15.4% (24 isolates), and 1.7% (two isolates), respectively. Sixteen isolates resistant to pydiflumetofen had N230I and one isolate had P225F in the Sdh-B, conferring moderate or high resistance to pydiflumetofen. One highly resistant isolate also had a substitution of asparagine to serine at codon 87 of Sdh-C. Isolates were confirmed to be resistant to pydiflumetofen in detached fruit assays. The authors suggest that due to low levels of resistance, the product might currently be a good choice for managing *Botrytis* fruit rot in Florida, but caution that resistance management strategies should be applied.

In another study, Machado et al. (2023) report results of multiple field trials in Brazil for Fusarium head blight (FHB) control. From these trials, a total of 227 isolates belonging to the *Fusarium graminearum* species complex were obtained from symptomatic wheat heads. The majority of the 227 isolates (64%) were of the 15-(A)acetyl-deoxynivalenol (DON), 29% of the nivalenol (NIV) and 4% of the 3-ADON genotype. EC_{50} values of a subsample ranged from 0.0004 to 3.0 and from 0.91 to 2.65 μg/ml for tebuconazole and carbendazim, respectively. Isolates of the 15-ADON genotype were less sensitive to tebuconazole compared to NIV + 3ADON. Evidence of lower sensitivity for both fungicides were detected. The study shows the frequency of the isolates less sensitive to tebuconazole and carbendazim increased over time from 2 and 4% to 24 and 95%, respectively. Control efficacy was generally lower in plants inoculated with less-sensitive isolates. A greater number of less-sensitive individuals were recovered from plants inoculated with a mixture with a sensitive isolate and sprayed with either fungicide. The authors conclude that the presence of less sensitive isolates may be associated with the frequent reports of decline in control efficacy for both fungicides.

In summary, microbial resistance, especially fungal resistance to fungicides, poses a significant challenge for agricultural production. Increased resistance to fungicides in pathogens can result in failures to control plant diseases and substantial economic losses in agriculture. Thus, managing this resistance and constant monitoring of product efficacy over time is important. Targeted research in this area may expand management options and prevent control failures and loss of efficiency of important active ingredients. Therefore, it is crucial to adopt proactive measures to monitor and mitigate microbial resistance, promoting responsible use of fungicides in agriculture and the development of new plant disease control strategies. Investments in research and education are essential to address this global challenge and ensure the long-term sustainability of agricultural systems.

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