JOURNAL OF AGRICULTURE AND PLANT SCIENCES, JAPS, Vol 23, No. 1, 2025

Manuscript received 28.05.2025
Accepted: 14.08.2025

In print: ISSN 2545-4447
On line: ISSN 2545-4455
doi: https://doi.org/10.46763/JAPS2523141k
Original scientific paper

THE SUCCINATE DEHIDROGENASE INHIBITOR FUNGICIDES: FUNGAL RESISTANCE AND ITS MANAGEMENT

Biljana Kovacevik[1*], Sasa Mitrev[1], Emilija Arsov[1], Natalija Markova Ruzdik[2], Daniela Todevska[2], Fidanka Trajkova[3]

[1]Department for Plant Protection and Environment, Faculty of Agriculture, Goce Delcev University, Stip, Krste Misirkov, 10A, 2000, Stip, Republic of North Macedonia
[2]Department for Plant Production, Faculty of Agriculture, Goce Delcev University, Stip, Krste Misirkov, 10A, 2000, Stip, Republic of North Macedonia
[3]Department for Plant Biotechnology, Faculty of Agriculture, Goce Delcev University, Stip, Krste Misirkov, 10A, 2000, Stip, Republic of North Macedonia

**Corresponding author: biljana.kovacevik@ugd.edu.mk*

Abstract

Effective disease management is essential to mitigate the rapid emergence of resistant pathogen populations. An important group of fungicides that play a pivotal role in the integrated management systems, among others, also because of their low environmental toxicity, are succinate dehydrogenase inhibitors, which act by binding to the mitochondrial complex II of the respiratory system. Unlike first-generation SDHIs (e.g., carboxin and oxycarboxin), which exhibit high efficacy against basidiomycetes, newer compounds in this class (e.g., cyclobutrifluram, furametpyr, and inpyrfluxam) demonstrate broad-spectrum activity against a wide range of fungal species. However, their repeated and inadequate application strategies, can exert strong selection pressure, favoring the development of resistant fungal genotypes, which may ultimately compromise fungicide efficacy. This review examines both historical and recent advancements in understanding the molecular mechanisms underlying SDHI resistance, as well as other factors influencing the evolution of resistance. In addition, it provides an insight into strategies for the effective use of newly developed SDHI molecules and highlights key research directions for combating resistance in the future.

Key words: *SDHI fungicides, resistance, plant protection, mode of action, fungicidal activity.*

INTRODUCTION

According to FRAC, fungicides that inhibit the succinate dehydrogenase (SDH) enzyme belong to the complex II inhibitors and are classified in group 7, which is comprised of 24 compounds that belong to 12 chemical groups (Tab. 1) (FRAC, 2024). Additionally, complex II inhibitors are also useful acaricides, insecticides, nematocides, and medicinal fungicides. Some of them are showing very high degrees of species selectivity (Earley, 2019). Shortly, after their introduction on the market, SDHI fungicides significantly impacted crop protection and by 2015 achieved nearly 8% of the total pesticide market, generating approximately €1 billion in turnover (Hermann & Stenzel, 2019). The first generation of fungicides that act as succinate dehydrogenase inhibitors (SDHI) belong to the chemical group of carboxamides and have a general structure of anilides (phenylamides) (R–C (=O)–N (–R')– C 6 H 5). The key factor enabling long-term research on these compounds is their relatively low toxicity, as most of them exhibit

LD_{50} values above 1500 mg/kg in land vertebrates. Another driver of sustained research interest in SDHI is the limited but promising fungicidal spectrum of carboxamide early compounds, and along with their structural flexibility, led to extensive exploration of both carbocyclic and heterocyclic scaffolds with various functional group substitutions. The advances in recognizing and understanding the enzyme target's structure and the mechanism of action of carboxylic amides have underscored the ongoing scientific and commercial focus on SDH inhibition. The earliest compounds in this class of fungicides were carboxin (1968) and oxycarboxin (1971), active mainly against basidiomycete pathogens (Von Schmeling & Kulka, 1966). In the next period (1971 – 1997), other SDHI such as benodanil, fenfuram, flutolanil, furametpyr, mepronil, and thifluzamide were introduced on the market. These SDHI fungicides possess limited activity against other pathogens except basidiomycetes. Following the first generation of SDHI molecules, the discovery of boscalid in 2003 with an increased spectrum of activity and potency heralded the age of synthesis of new SDHI molecules (Glättli et al., 2011). Novel SDHI fungicides (isofetamid, fluopyram, isoflucypram, pydiflumetofen, pyraziflumid, fluorine substituted pyrazol-4-yl-carboxamides, and phenyl-cyclobutyl-pyridineamide- cyclobutrifluram), has been established on the market, since 2008 are characterized with an extremely broad spectrum of activity not only against Basidiomycetes, but also against various Deuteromycetes and Ascomycetes and recognized by their application rates in many different crops (Tab. 1) (Stammler et al., 2007).

BIOLOGICAL ACTIVITY AND APPLICATION

The first discovered compound of SDHI fungicides, carboxin, was used predominantly for seed dressing against Rhizoctonia spp. in cereals and other crops, and it was also effective against smuts (*Ustilago spp.* and *Tilletia spp.*). Oxicarboxin, the structurally similar compound to carboxin, was used predominantly to control rust diseases, especially in cereals, ornamentals, and turf (Glättli et al., 2011). The next two compounds discovered, namely, benodanil and fenfuram, were shown to have similar activity and were also used for seed dressing. Mepronil and flutolanil are benzoic acid derivatives with very similar structures and activity that differ only by the fluorination of a methyl group in flutolanil. The activity of these compounds is similar to that of the previous ones, with application not only via seed treatment, but also with soil incorporation, or foliar spray (Stammler et al., 2015). The thiazole carboxamide–thifluzamide is still in use in some countries such as Asia and Latin America. It is used to control soil-borne and foliar fungal diseases caused by *Basidomycetes spp.*, particularly *Rhizoctonia solani*. One of its most important uses is to control Sheath blight in rice, Limb rot in peanuts, and Black scurf in potatoes. The largest subgroup of SDHIs, the pyrazole-4- carboxamides, comprises eleven active compounds. Their broad spectrum of activity is due to the presence of a pyrazole ring substituted at the 4-position with a carboxamide group. They are especially used in cereals to control *Septoria*, Rusts, Net blotch, Powdery mildew, and *Rhynchosporium*, and also can be effective against *Botrytis*, *Alternaria*, and *Sclerotinia* in vegetables and fruits (Dong et al., 2013). Fluopyram and cyclobutrifluram are unique among SDHIs with dual action as broad-spectrum fungicides and nematicides (Flemming et al., 2025; Schleker et al., 2022). Their fungicidal properties are documented against *Botrytis spp.*, *Alternaria spp., Sclerotinia spp.*, Powdery mildews, Anthracnoses, and Septorioses in grapes, apples, strawberries, cucurbits, tomatoes, and cereals (Flemming et al., 2025; MDA, 2012). In addition, they are also recognized for nematocide activity against the most important nematode genera of vegetables such as *Meloidogyne spp.*, *Pratylenchus spp.*, and *Heterodera spp.*, which attack soybean, sugar beets, and canola (Schleker et al., 2022). Isofetamid is a systemic fungicide used primarily to control *Botrytis*, *Monilinia*, and *Sclerotinia* diseases, in high-value horticultural crops such as grapes, strawberries, lettuce, tomatoes, beans, stone fruits, and ornamentals (Nishimi et al., 2024). Isoflucypram belongs to a novel subclass of SDHIs, characterized by an N-cyclopropyl substitution, which confers an altered binding mode at the ubiquinone binding site of the succinate dehydrogenase enzyme. This structural innovation contributes to its high intrinsic activity and broad-spectrum

effectiveness. It provides robust protection against key cereal diseases, including Septoria leaf blotch, Yellow and Brown rust, Eyespot, and Powdery mildew (Desbordes et al., 2020). Another SDHI, introduced by Syngenta in 1916, is pydiflumetofen, which has a unique chemical structure of N-methoxy-(phenyl-ethyl)-pyrazole-carboxamide. In pydiflumetofen, the amide nitrogen (N–) is substituted with a methoxy group (–OCH_3) and a phenyl-ethyl side chain in the base structure represented by a pyrazole ring with a carboxamide group (-CONH-) at the 4-position (Padmathilake et al., 2022). The polarity and electronic effects of the N-methoxy group enhance lipophilicity and binding interactions, which enhance the interaction with the SDH enzyme and improve systemic movement in plant tissues (Walter, 2016). Pydiflumetofen, just as other novel SDHI fungicides, poses a broad-spectrum activity against powdery mildew, septoriosis, cercospora leaf spot; *Alternaria*, scab and grey mould in various crops such as soybeans, cereals, vegetables, including carrots, parsnip, corn, peanut, cucurbits, potato, grapes, melon, etc. (Padmathilake et al., 2022).

MODE OF ACTION

Succinate dehydrogenase inhibitors are a group of fungicides that target a crucial step in fungal energy metabolism. They exert their fungicidal activity by interfering with the mitochondrial respiratory chain, specifically targeting the succinate dehydrogenase (SDH) enzyme, which is also known as Complex II or succinate-ubiquinone oxidoreductase. It is the smallest complex in the mitochondrial respiratory chain and a functional part of the tricarboxylic acid (TCA) cycle, also known as the Krebs cycle, and also the mitochondrial electron transport chain (ETC) (Glättli et al., 2011). The complex comprises of four primary proteins (subunits): SdhA, SdhB, SdhC, and SdhD. The catalytic subunit SdhA is a flavoprotein responsible for succinate oxidation and contains a covalently bound FAD cofactor. An iron-sulfur protein SdhB contains three iron-sulfur clusters ([2Fe-2S], [4Fe-4S], and [3Fe-4S]) responsible for transferring electrons from $FADH_2$ to ubiquinone (Skinner et al., 1998). The membrane-bound subunits SdhC and SdhD form part of the cytochrome b and embed the complex in the inner mitochondrial membrane. These subunits contribute to the formation of the ubiquinone-binding site (Q-site), often in close proximity to the [3Fe-4S] cluster and a heme b prosthetic group. SDH act by catalyzing the oxidation of succinate to fumarate. This reaction also leads to reduction of flavin adenine dinucleotide (FAD), generating $FADH_2$ in the TCA cycle. In its second role, SDH transfers electrons from $FADH_2$ to ubiquinone (coenzyme Q), which is then reduced to ubiquinol. This transfer contributes to the proton motive force used by ATP synthase to generate ATP through oxidative phosphorylation (Cecchini, 2003). In fact, SDH represents a key link between substrate oxidation and energy generation (Keon et al., 1991). Modern SDHIs are defined by their capacity to interact with the ubiquinone-binding site (Q-site) located in the SdhB, SdhC, and SdhD subunits of the SDH enzyme complex. By blocking this site, SDHIs prevent the normal transfer of electrons from $FADH_2$ to ubiquinone and prevent the reduction of ubiquinone, disrupting the electron transport chain and leading to energy depletion in fungal cells. Normally, the oxidation of succinate, generates electrons that are passed through FAD and Fe-S clusters to ubiquinone. In the presence of SDHIs, electrons are unable to move through the electron transport chain because the SDHIs occupy the same site as ubiquinone, acting competitively or non-competitively, impairing the proton gradient across the mitochondrial membrane (Sierotzki and Scalliet. 2013). This leads to a failure in oxidative phosphorylation and a consequent decrease in ATP synthesis.

Table 1. Classification and representatives of SDHI fungicides (FRAC Code 7) according to the Fungicide Resistance Committee (FRAC, 2024).

Chemical or biological group	Common name	Company and year of first registration	Status in EU
phenyl-benzamides	benodanil	BASF, 1974	not approved
	flutolanil	Nihon Nohyaku Co., 1986	15/06/2025
	mepronil	Kumiai Chemical Industry Co., 1981	not approved
henyl-oxo-ethyl thiophene amide	isofetamid	ISK Biosciences, 2016	15/09/2026
pyridinyl-ethyl-benzamides	fluopyram	Bayer, 2012	30/06/2026
phenyl-cyclobutyl-pyridineamide	cyclobutrifluram	Syngenta, 2022	ni*
furan-carboxamides	fenfuram	Shell, 1974 (now Bayer CropScience)	not approved
oxathiin- carboxamides	carboxin	Uniroyal Chemical Co., 1968	not approved
	oxycarboxin	Uniroyal Chemical Co., 1971	not approved
thiazole- carboxamides	thifluzamide	Monsanto, 1997 (now Dow AgroSceince)	not approved
pyrazole-4-carboxamides	benzovindiflupyr	Syngenta, 2014	02/08/2026
	bixafen	Bayer, 2011	31/05/2025
	fluindapyr	FMC Corporation, 2019	pending
	fluxapyroxad	BASF, 2011	31/05/2025
	furametpyr	Sumitomo Chemicals, 1997 BASF, 2021	ni*
	inpyrfluxam	Sumitomo Chemical, 2020	pending
	isopyrazam	Syngenta,2010	not approved
	penflufen	Bayer, 2012	31/05/2025
	penthiopyrad	Mitsui, 2008	31/05/2025
	sedaxane	Syngenta, 2011	31/10/2027
N-cyclopropyl-N-benzyl-pyrazole-carboxamides	isoflucypram	Bayer, 2019	pending
N-methoxy-(phenyl-ethyl)-pyrazole-carboxamides	pydiflumetofen	Syngenta, 2016	pending
pyridine- carboxamides	boscalid	BASF, 2003	15/04/2026
pyrazine-carboxamides	pyraziflumid	Nihon Nohyaku Co., Ltd.,2018	ni*

*ni – no information

So, fungal pathogens, which rely heavily on efficient mitochondrial respiration, such as the necrotrophic fungi *Botrytis cinerea*, *Alternaria spp., Fusarium spp., Sclerotinia sclerotiorum*, and hemibiotrophic *Zymoseptoria tritici*, some *Fusarium spp*., etc., are particularly vulnerable to this disruption. These fungi produce large amounts of cell wall-degrading enzymes, toxins, and secondary metabolites to kill host cells and feed on dead tissue. This requires high levels of energy (ATP) to support growth, sporulation, enzymatic degradation of plant tissues, and evasion of host defenses. High levels of energy are especially needed during spore germination and hyphal invasion, when glycolysis alone is insufficient for ATP production. Mitochondrial respiration is essential for these biosynthetic processes and for adapting to oxidative stress from plant defenses (Avenot & Michailides, 2010). The structural diversity among SDHIs allows for a broad spectrum of activity against various fungal pathogens.

MECHANISMS OF RESISTANCE

Fungal resistance to SDHI fungicides primarily arises through the target-site mutations in the succinate dehydrogenase (SDH) enzyme complex. These mutations alter the structure of the SDH complex in ways that reduce or prevent the binding of SDHI fungicides, while still allowing the enzyme to function in fungal respiration, and usually occur in SdhB, SdhC, and SdhD subunits. It is considered that the single-nucleotide polymorphisms (SNPs) in the genes encoding these subunits are responsible for amino acid substitutions (Broomfield & Hargreaves, 1992). Substitution of histidine (H), especially at position 272 is the most common mutation in the SdhB subunit associated with SDHI resistance (Tab. 2). Positively charged histidine acts as a proton donor or acceptor around physiological pH due to its pKa near 7, and it can be substituted with arginine (R), tyrosine (Y), leucine (L), vaniline (V), etc. Substitution with arginine (H272R) is the most frequently reported SdhB mutation. This mutation is commonly found in field isolates of Botrytis cinerea obtained from various crops (FRAC, 2021a). Substitution with leucine and tyrosine is also reported in *B. cinirea* (FRAC, 2021a). Similar histidine substitutions at position 272 have been observed in *Botrytis ecliptica, Stemphylium vesicarium, Podosphaera xanthii, Corynespora cassiicola, Didymella bryoniae,* and *Pyrenophora teres* (FRAC, 2015, 2021 a,b). Substitutions of asparagine (N) in the SdhB subunit, particularly at positions 225 or 230, have been documented in several fungal pathogens. The polar, uncharged amino acid asparagine is responsible for hydrogen bonding and structural stabilization in Sdh. Its substitution by more hydrophobic or charged residues can disrupt the SDHI binding pocket in SDH, leading to SDHI fungicide resistance. Aspargine substitutions at SdhB sections are identified at *B. cinirea* (N225T; N230I), *Zymoseptoria tritici* (N86S), *D. bryoniae* (N86S; N225S), and *Alternaria alternata* (N225S) (Tab. 3). Another well-documented mutation in SdhB subunit include proline substitutions, particularly at position 225 (Tab. 3). Proline has a rigid, cyclic structure that introduces kinks or turns in protein backbones (Hutchinson & Thornton, 1994). Substituting proline with a more flexible or chemically different amino acid (e.g., phenylalanine, leucine) can significantly alter the 3D structure of the SDH binding pocket. Such mutations are well documented in *B. cinerea* (P225H, P225T, P225L, P225F) and *D. bryoniae* (P225N) and are linked to multiple resistance against SDHIs such as boscalid, fluopyram, and isopyrazam (Bi et al., 2022; Liu et al., 2024). While mutations in SdhB are more frequently reported, SdhC mutations are increasingly recognized, especially in fungi like *Z. tritici, Pyrenophora teres, Alternaria spp., and B. cinerea*. Substitutions of histidine or serine with arginine (C-H134R; C-S135R) are among the most common mutations in Z. tritici. These mutations are well known to reduce binding of fluxapyroxad and bixafen and are frequently detected across Europe and other wheat-producing regions (Rehfus et al., 2017, 2018). Other frequently detected mutations in the SdhC subunit are recognized in *P. teres* (C-N75S, C-G79R, C-H134R, C-S135R) (Stammler et al., 2014). Mutations in SdhC in B. cinerea are less common but are documented on glicine (C-G84V, C-G79R), asparagine (C-N75S), and alanine (C-A85V) (Konstantinou et al., 2014; Leroux et al., 2010). Shao et al. (2022) conferred the C-A78V mutation in Fusarium. graminearum as precursor for pydiflumetofen resistance. These mutations are usually found in combination with SdhB mutations (Veloukas et al., 2014). C-H134R

mutation is documented in *A. alternata* isolated from pistachio (FRAC, 2021a) and SdhC-H151R in *Venturia inaequalis* (FRAC, 2021a). Mutations in SdhD subunit typically confer lower levels of resistance compared to SdhB and SdhC subunits, but they are still recognized to contribute to multi-side resistance when present alongside other mutations. Substitution of aspartic (D) with glutamic acid (E) in SdhD subunit is also frequently detected mutation in *Z. tritic*i, though its effect on resistance is usually moderate (Rehfus et al., 2018). Mutations in SdhD subunit are also documented in *P. teres (*SdhD-D124N/E, SdhD-H134R, SdhD-D145G), *Aspergilus orizae* (SdhD-D124E), B. cinerea (D-H132R), *A. alternata* (D-D123E, D-H133R), *A. solani* (D-H133R), *C. cassiicola* (D-G109V), *Sclerotinia sclerotiorum* (D-H132R) (FRAC, 2015; 2021a,b), etc. (Tab. 3).

While target-site mutations are the primary mechanism, evidence suggests the existence of additional or indirect resistance mechanisms that don't involve obvious genetic changes in SDH genes. These non-target site mutations include (i) Overexpression of Efflux Pumps and (ii) Metabolic Detoxification. Fungal cells have efflux pumps, which are proteins embedded in the cell membrane that actively transport toxic substances out of the cell. These pumps are part of the ATP-binding cassette (ABC) transporter family, and they use energy (ATP) to pump out harmful compounds, including fungicides. If a fungus produces more of these efflux pumps, it can remove SDHI fungicides from the cell before they reach the mitochondria, where their target (the SDH enzyme) is located (Sierotzki and Scalliet, 2013; Earley F., 2019). This reduces the effective concentration of the fungicide inside the cell, decreasing its toxicity. These mechanisms don't block SDHIs entirely but make them less effective because of the lower doses of SDHIs present in the fungal cell. Metabolic detoxification occurs in some fungi that produce detoxifying enzymes that can chemically modify or degrade fungicides, making them harmless before they can reach their site of action. These enzymes, for example, include cytochrome P450 monooxygenases, glutathione-S-transferases, or some other metabolizing enzymes (Sierotzki and Scalliet, 2013). Fungi with non-target resistance may survive low-dose treatments and typically provide low-level and partial resistance, eventually leading to more resistant populations. In addition, not all mutations are equally favorable. Some resistant mutants have reduced fitness, meaning they grow more slowly or are less competitive in the absence of the fungicide. However, some mutations confer resistance with little or no fitness cost, making them more likely to spread in field populations (Avenot & Michailides, 2010). Repeated use of SDHIs, especially as solo applications or with incomplete rotations, selects for resistant individuals. Once established, resistant strains can spread via spores, especially in polycyclic diseases like *Zymoseptoria tritici* (Rehfus et al., 2017). In some fungi, multiple mutations can occur in parallel, leading to a range of resistance levels depending on the specific SDHI used. For example, if non-target site mutations are combined with target-site mutations, they can amplify the resistance level. As it was mentioned before, even though all SDHI fungicides target the same site (ubiquinone-binding pocket) of the SDH enzyme, they don't all bind in exactly the same way. The main reason for this is because different SDHIs have different chemical structures. As a result, they interact with different amino acids within the Q-site or bind in slightly different orientations. When a mutation alters the shape or chemistry of the Q-site, some SDHIs may be more affected than others. For example, it is found that the mutation like SDHC-H134R greatly reduce the binding of boscalid, causing high resistance. The mutation also lightly affects the binding of fluopyram, leading to moderate or no resistance. This is because the new amino acid blocks or distorts only part of the binding pocket that boscalid needs, but not all SDHIs use the exact same part of the binding pocket (Avenot et al., 2011). As a result of this, the cross-resistance patterns in fungi can vary. Mutations in SDHC, especially at positions 84 and 134, are frequently associated with broad-spectrum resistance, which usually affects many or all SDHIs. The H134R mutations in *Alternaria alternata, Alternaria solani, and Didymella tanaceti,* have been linked to very high resistance levels to SDHI fungicides like boscalid and penthiopyrad (Förster et al., 2022; Bauske et al., 2017; Pearce et al., 2019). Some mutations may confer resistance to one SDHI (e.g., boscalid), but not necessarily to others (e.g., fluopyram or isopyrazam) (Tab. 2). Fluopyram often retains some activity even when other SDHIs fail due to a different binding conformation (Yamashita

& Fraaije, 2018). Cyclobutrifluram, the new-generation SDHI shows slightly different binding, but broad-spectrum mutations (A84V, H134R) and still confer high resistance (Li et al., 2023 a,b). Resistance mechanisms to SDHIs have been intensively studied in *B. cinerea*. The investigations confirmed that this ascomycetous pathogen developed serious resistance to multiple SDHIs such as boscalid, fluopyram, fluxapyroxad, and penthiopyrad in various crops (cucumber, grape, tomato, strawberry etc.).

Table 2. Common SDHI Resistance Mutations and Cross-Resistance Profiles to some SDHI fungicides (FRAC, 2023).

	SDHB-H267Y/L	SDHC-H134R/Y/Q	SDHC-S135R/N	SDHD-D123E/N	SDHC-A84V	SDHB-N225T	SDHC-G79R
Boscalid	High	High	High	Low–Moderate	High	High	High
Fluopyram	Moderate–Low	Variable	Moderate	Low	High	Low–Moderate	Moderate
Isopyrazam	Moderate	Moderate	High	Low	High	Low	High
Bixafen	Moderate	Moderate	High	Low	High	Moderate	High
Cyclobutrifluram	Moderate	High	High	Low	High	Low–Moderate	Moderate
Isofetamid	Low–Moderate	High	Moderate–High	Low	High	Low	High
Benzovindiflupyr	Moderate	High	High	Low	High	Moderate	High
Flutolanil	High	High	Moderate	Low	High	High	High

H – histidine; A -alanine; R – arginine; N – aspargine; D – aspartic acid; C – cysteine; E – glutamic acid; Q – glutamine; G – glycine; I – isoleucine; L – leucine; V – valine; Y – tyrosine, T – threonine; S – serine.

RESISTANCE MANAGEMENT

Fungal resistance development is significantly accelerated by the continuous use of fungicides with specific modes of action. However, using them occasionally alongside with unrelated fungicides reduces this risk. Resistance management strategies should balance long-term fungicide effectiveness with meeting farmers' needs and ensuring profitability for manufacturers. These strategies must be applied consistently over large areas, requiring cooperation from all involved supply companies and acceptance by farmers (Corkley et al., 2021). According to the specific measures related to SDHIs, they should always be applied preventively and in rotation with fungicides from different resistance groups. In this case, the total number of SDHI applications should not exceed three per year. If more than 12 fungicide applications per season are considered according to a specific protection program, SDHIs should comprise no more than one-third (33%) of the total applications. When combined

with other fungicides in a mixture, no more than two consecutive SDHI-containing applications should be applied. Also, they should include a pesticide or pesticides with a different mode of action and with proven efficacy against the target disease. When SDHIs are used alone and in mixtures throughout a season, the total number of applications containing SDHI fungicides should not exceed 50% of all fungicide applications for the season. Also, it is recommended foliar application in cereals to be in mixtures. When an SDHI fungicides are used as a seed treatment against low-risk foliar pathogens on cereals, there should be no implications regarding their use, while for pathogens with moderate or high resistance risk, application should be counted against the total number of applications (Tab. 2) (FRAC, 2022). When managing the resistance to SDHIs, field investigations and detection of the resistance level are of crucial importance. In case the field isolates show full or slightly decreased sensitivity and no impact on field efficacy is observed, the pathogen is considered as low-risk for the investigated area, and the general guidelines for the use of SDHI fungicides are considered sufficient (Tab. 3).

Table 3. List of fungal species with documented resistance to SDHI fungicides, the Sdh mutations identified, and the origin of the resistant isolates

Pathogen	**Sdh subunit**			**Area with high risk of resistance[1]**	**Reference**
	SdhB	**SdhC**	**SdhD**		
Alternaria alternata	H277Y/R, H277Y/R/L N235D/T/E/G, P230A/R/I/F/D	H134R, S135R	D123E, H133R H133P	Spain	Avenot et al.,2008
A. brassicae	ni	ni	ni	Germany	FRAC, 2024
A. brassicicola	ni	ni	ni	Germany	FRAC, 2024
Alternaria solani	H277Y/R, H278R/Y	H134R/Q	H133R D123E	Denmark, Belgium, Germany, the Netherlands Sweden	FRAC, 2021a
Aspergillus oryzae	H249Y/L/N,	T90I,	D124E	Lab	Shima et al., 2009
Aspergillus flavus		G91R			Yin et al., 2023
Botrytis cinerea	P225L/T/F, H272Y/R/L/V, N230I, K283N	A85V, A187F, G37S, G85A, I93V, M158V, P80H, V168I	H132R, V9A, I189L	Germany, Poland, Belgium, United Kingdom, Sweden, Portugal, Greece, Denmark, Norway	Yin,et al., 2011 Veloukas et al., 2011 Angelini et al., 2010 Samaras et al., 2016
Botrytis elliptica	H272Y/R			ni	FRAC, 2015
Blumeriella jaapii	H260R, I262V	S84L, N86S		ni	Yin et al., 2023
Corynespora cassiicola	H278Y/R, I280V	S73P, N75S	S89P, G109V V152I D95E, H105R	Brasil, China	Miyamoto et al., 2010 Yin et al., 2023 FRAC,2023
Clarireedia spp.	H267R	G91R, G150R		ni	Yin et al., 2023
Clarireedia homoeocarpa		G91R		ni	Yin et al., 2023
Didymella bryoniae	H277R/Y				Avenot et al., 2011

Didymella tanaceti	H277Y, I279V	S73P, G79R, H134R/Q, S135R	D112E, H122R	ni	Yin et al., 2023
Erysiphe necator	H242Y/R I244V B-H242R+C-G169S B-I244V+C-G169S	G169D/S A83V		Austria, France, Germany, Hungary, Portugal, Spain, Switzerland, Italy, Czech Republic, Slovakia, Greece, Croatia, Tuerkiye, Ukraine	Cherrad et al., 2018 FRAC, 2024
Fusarium graminearum		T73I, A78V, R86C		China	Yin et al., 2023
Monilinia spp.				No impact on field efficacy is reported	FRAC,2024
Phakopsora pachyrhizi		I86F N88S/D, H154R, G92R		Brasil, Paraguay	Yin et al., 2023 FRAC,2024
Podosphaera fusca		A86V, G151R, G172D	S121P, H137R	ni	Yin et al., 2023
Podosphaera xanthii	H272Y/R/L/V			France, Greece, Italy, the Netherlands, and Portugal	FRAC, 2021a
Pyrenophora teres	H277Y	N75S, G79R, H134R, S135R, R64K K49E	D124N/E, H134R, D145G; H134Y G138V	North-Western Europe (France, Germany, Ireland), United Kingdom	Stammler et al., 2014
Pyricularia oryzae	H245Y			ni	Yin et al., 2023
Puccinia hordei		I87F		No impact on field efficacy is reported	FRAC, 2024
Puccinia horiana		I88F		No impact on field efficacy is reported	Yin et al., 2023
Ramularia collo-cygni	T267I, N224T	H146R/L, H153R N164H, G167C, V184L N87S G91R G171D		France, Germany, Ireland, Slovenia, the Netherlands, UK	Yin et al., 2023 FRAC, 2024
Rhizoctonia solani	H249Y		F48L	ni	Yin et al., 2023
Sclerotinia sclerotiorum	H273Y,	H146R,	H132R	No impact on field efficacy is reported	Glättli et al., 2009
Sphaerotheca fuliginea	ni	ni	ni	France, Greece, Italy, the Netherlands and Portugal	FRAC, 2024
Stemphylium vesicarium	P225L, H272Y/R			Portugal, Italy	FRAC, 2021a,b
Ustilago maydis	H257L			No impact on field efficacy is reported	Keon et al., 1991 FRAC, 2024

Venturia inaequalis	T253I	H151R C-N85S		No impact on field efficacy is reported	FRAC, 2021a
Zymoseptoria tritici	N225T, N225I, H267Y/R/L, I269V,	T79N, W80S, N86S A84V, H152R, T79I, N86K, G90R,	H129E,	France, Germany, Ireland, Italy, United Kingdom	FRAC, 2021a Skinner et al., 1998; Scalliet et al., 2010; Scalliet et al., 2011; Fraaije et al., 2011

[1]according to FRAC; H – histidine; A -alanine; R – arginine; N – aspargine; D – aspartic acid; C – cysteine; E – glutamic acid; Q – glutamine; G – glycine; I – isoleucine; L – leucine; V – valine; Y – tyrosine, T – threonine; S – serine; ni – no information;

FUTURE PERSPECTIVES

Although routine monitoring and good agricultural practices can guide SDHI application strategies and delay the establishment of resistant populations, the issue is far more complex. The variation in sensitivity is common between species and among isolates from different geographic locations (Sierotzki & Scalliet 2013). Field and laboratory studies revealed the presence of naturally resistant fungal genotypes and cross-resistance patterns between SDHIs, as well as complex different t side mutations. Notably, in *Zymoseptoria tritici,* a major wheat pathogen, resistance to SDHIs is not solely limited to point mutations in the SDH subunits. Recent studies have identified two functionally redundant paralogs, SdhC and alt-SdhC, in certain field isolates (Steinhauer et al., 2019; Yin et al., 2023). These alternative subunits can be differentially expressed and are associated with variable sensitivity to SDHIs. A particularly striking example of this complexity involves high-level resistance phenotypes to the amide subclass of SDHIs, which have been linked to the insertion of transposable elements 182 base pairs upstream of the alt-SdhC start codon. This insertion appears to enhance the expression of *alt-SdhC,* which encodes a unique Qp-site residue that reduces SDHI binding efficacy (Stammler et al., 2015). Such genomic plasticity underscores the importance of considering both target-site and non-target-site resistance mechanisms in resistance management strategies. To better predict and counteract these evolving threats. Functional genomics plays a vital role in uncovering new resistance determinants and tracing their evolutionary trajectories. Insights from transcriptomic and epigenomic data can illuminate how regulatory changes, gene duplications, or horizontal gene transfers contribute to resistance. Moreover, this information feeds into predictive models of resistance emergence and spread, helping design more durable disease control strategies. In parallel, structure-guided design of next-generation SDHIs that can accommodate mutations or target alternative SDH configurations offers promising avenues for overcoming resistance. Continued development of advanced molecular diagnostics, including high-throughput sequencing, allele-specific PCR, and CRISPR-based detection systems, is critical for the early identification of resistant genotypes, particularly those carrying naturally occurring variants like *alt-SdhC.*

CONCLUSION

Succinate dehydrogenase inhibitors are frequently used in modern crop protection programs, valued for their broad-spectrum activity and relatively low environmental impact. However, their extensive and repeated use has led to the emergence and proliferation of resistant fungal populations, posing a growing threat to sustainable crop protection. Resistance is primarily driven by point mutations in the SdhB, SdhC, and SdhD subunits, which reduce fungicide binding affinity to the target site. The degree of resistance varies depending on the specific amino acid substitutions and their structural effects. Beyond these canonical mechanisms, other factors such as efflux pump overexpression, gene duplication, and regulatory

mutations, including transposon insertions near resistance-associated genes, make the situation more complex. Such resistance mechanisms have been documented in several economically significant pathogens, including *Zymoseptoria tritici, Botrytis cinerea,* and *Alternaria alternata*.

The continued reliance on SDHIs exerts strong selection pressure on pathogen populations, promoting the spread of resistance alleles at local, regional, and potentially global scales. The dynamics of resistance evolution are influenced by fungicide application strategies, pathogen biology, and the fitness costs associated with resistance mutations. Addressing this challenge requires a multidisciplinary approach. Integrating advanced molecular diagnostics, functional genomics, and population biology with agronomic practices and rational fungicide design will be essential. Improved resistance monitoring, deployment of integrated disease management strategies, and the development of next-generation SDHIs capable of overcoming existing resistance will help preserve the long-term efficacy of this important fungicide class. Sustained research and coordinated stewardship are vital to safeguarding crop yields and ensuring food security in the face of evolving fungal threats.

REFERENCES

Angelini, R.M.D., Habib, W., Rotolo, C., Pollastro, S., & Faretra, F. (2010). Selection, characterization, and genetic analysis of laboratory mutants of *Botryotinia fuckeliana (Botrytis cinerea)* resistant to the fungicide boscalid. *European Journal of Plant Pathology, 128, 185-199.*

Avenot, H.F., Thomas A., Gitaitis, R.D., Langston, Jr. D.B., & Stevenson, K.L. (2011). Molecular characterization of boscalid and penthiopyrad resistant isolates of Didymella bryoniae and assessment of their sensitivity to fluopyram. Pest Management Science, doi: 10.1002/ps.2311.

Avenot, H.F., & Michailides, T.J. (2010). Progress in understanding molecular mechanisms and evolution of resistance to succinate dehydrogenase inhibiting (SDHI) fungicides in phytopathogenic fungi. *Crop Prot.,* 29, 643 - 651.

Avenot, H.F., Sellam, A., Karaoglanidis, G., & Michailides, T.J. (2008). Characterization of mutations in the iron-sulphur subunit of succinate dehydrogenase correlating with boscalid resistance in *Alternaria alternata* from California pistachio. *Phytopathology,* 98, 736-742.

Bauske, M.J., Mallik, I., Yellareddygari, S.K.R., & Gudmestad, N.C. (2017). Spatial and Temporal Distribution of Mutations Conferring QoI and SDHI Resistance in *Alternaria solani* Across the United States. Plant Disease, 102(2), 349–358. https://doi.org/10.1094/pdis-06-17-0852-re

Bi, Q., Lu, F., Yang, K., Wu, J., Zhang, S., Han, X., Wang, W., & Zhao, J. (2022). Baseline Sensitivity and Resistance of Botrytis cinerea to Penthiopyrad in Hebei Province, China. *Horticulturae,* 8(8), 686. https://doi.org/10.3390/horticulturae8080686

Broomfield, P.L.E., & Hargreaves, J.A. (1992). A single amino-acid change in the iron-sulphur protein subunit of succinate dehydrogenase confers resistance to carboxin in *Ustilago maydis. Curr. Genet*., 22,117-121.

Cecchini, G. 2003. Function and structure of complex II of the respiratory chain. *Annu. Rev. Biochem.,* 72, 77-109.

Cherrad, S., Charnay, A., Hernandez, C., Steva, H., Belbahri, L., & Vacher, S. (2018). Emergence of boscalid-resistant strains of *Erysiphe necator* in French vineyards. *Microbiological Research,* 216, 79–84. https://doi.org/10.1016/j.micres.2018.08.007

Corkley, I., Fraaije, B., & Hawkins, N. (2021). Fungicide resistance management: Maximizing the effective life of plant protection products. *Plant Pathology,* 71(1), 150–169. https://doi.org/10.1111/ppa.13467

Desbordes, P., Essigmann, B., Gary, S., Gutbrod, O., Maue, M., & Schwarz, H.G. (2020). Isoflucypram, the first representative of a new succinate dehydrogenase inhibitor fungicide subclass: Its chemical discovery & unusual binding mode. *Pest Management Science*, 76(10), 3340 – 3347. doi:10.1002/ps.5951

Dong, F., Chen, X., Xu, J., Liu, X., Chen, Z., Li, Y., Zhang, H., Zheng, Y. (2013). Enantioseparation and determination of the chiral fungicide furametpyr enantiomers in rice, soil, and water by high-performance liquid chromatography. *Chirality.,* 25(12), 904-9. doi: 10.1002/chir.22232.

Earley F. (2019). Fungicides Acting on Oxidative Phosphorylation. In: Modern Crop Protection Compounds (pp. 609 – 747). Wiley-VCH, Weinheim, Germany. ISBN 978-3-527-34089-7

Flemming, A., Guest, M., Luksch, T., O'Sullivan, A., Screpanti, C., Dumeunier, R., Gaberthüel, M., Godineau, E., Harlow, P., Jeanguenat, A., Kurtz, B., Maienfisch, P., Mondière, R., Pierce, A., Slaats, B., Smejkal, T., & Loiseleur, O. (2025). The discovery of Cyclobutrifluram, a new molecule with powerful activity against nematodes and diseases. *Pest Manag Sci,* 81, 2480-2490. https://doi.org/10.1002/ps.8730

Förster, H., Luo, Y., Hou, L., & Adaskaveg, J.E. (2022). Mutations in Sdh Gene Subunits Confer Different Cross-Resistance Patterns to SDHI Fungicides in Alternaria alternata Causing Alternaria Leaf Spot of Almond in California. *Plant Dis.*,106(7),1911-1918. doi: 10.1094/PDIS-09-21-1913-RE.

Fraaije, B.A., Bayon, C., Atkins, S., Cools, H.J., Lucas, J.A., & Fraaije, M.W. (2011). Risk assessment studies on succinate dehydrogenase inhibitors, the new weapons in the battle to control Septoria leaf blotch in wheat. *Molecular Plant Pathology,* 1364-3703. doi: 10.1111/j.

FRAC (2015). Minutes Of The 2014 SDHI Meeting Recommendations For 2015 V2. Available at https://www.frac.info/frac-teams/working-groups/sdhi-fungicides/#open-tour

FRAC (2021a). Minutes Of The 2021 SDHI Meeting 20 21Th Of January 2021 With Recommendations For 2021. Available at https://www.frac.info/frac-teams/working-groups/sdhi-fungicides/#open-tour

FRAC (2021b). Minutes Of The 2021 SDHI Meeting With Recommendations For 2021 Last Update October 2021. Available at https://www.frac.info/frac-teams/working-groups/sdhi-fungicides/#open-tour

FRAC (2022). FRAC Recommendations for SDHI fungicides. Available at https://www.frac.info/frac-teams/working-groups/sdhi-fungicides/#open-tour

FRAC (2023). Minutes Of The 2023 SDHI Meeting With Recommendations For 2023 From 17 18Th Jan and 20Th April 2023. Available at https://www.frac.info/frac-teams/working-groups/sdhi-fungicides/#open-tour

FRAC (2024). Fungal control agents sorted by cross-resistance pattern and mode of action. Fungicide Resistance Action Committee. Available at https://www.frac.info/media/kufnaceb/frac-code-list-2024.pdf

Glättli, A., Grote, T., & Stammler, G. (2011). SDH-inhibitors: History, biological performance and molecular mode of action. in: *Modern Fungicides and Antifungal Compounds,* (pp. 159-170). DPG, Braunschweig, Germany.

Glättli, A., Stammler, G., & Schlehuber, S. (2009). Mutations in the target proteins of succinate-dehydrogenase inhibitors (SDHI) and 14delta-demethylase inhibitors (DMI) conferring changes in the sensitivity – structural insights from molecular modelling. In *Proceedings of 9th International Conference on Plant Diseases* (pp. 670-681). Tours, France

Hermann, D., & Stenzel, K. (2019). FRAC Mode of action, Classification and Resistance Risk of Fungicides. In *Modern Crop Protection Compounds* (pp. 589 – 608). Wiley-VCH, Weinheim, Germany. ISBN 978-3-527-34089-7.

Hutchinson, E.G., & Thornton, J.M. (1994). The role of proline residues in protein structures. *Protein Science*, 3(11), 1861-1874.

Keon, J.P.R., White, G.A. & Hargreaves J.A. (1991). Isolation, characterisation and sequence of a gene conferring resistance to the systemic fungicide carboxin from the maize smut pathogen, Ustilago maydis. *Current Genetics,* 19, 475-481.

Konstantinou, S., Veloukas, T., Leroch, M., Menexes, G., Hahn, M., & Karaoglanidis, G. (2014). Population Structure, Fungicide Resistance Profile, and sdhB Mutation Frequency of Botrytis cinerea from Strawberry and Greenhouse-Grown Tomato in Greece. *Plant Disease,* 99(2), 240–248. https://doi.org/10.1094/pdis-04-14-0373-re.

Leroux, P., Chapeland, S., Desbrosses, A., & Gredt, F. (2010). Exploring mechanisms of resistance to respiratory inhibitors in field strains of Botrytis cinerea, the causal agent of gray mold. *Applied and Environmental Microbiology*, 76(19), 6615–6623. https://journals.asm.org/doi/full/10.1128/aem.00931-10

Li, Y., Tang, Y., Xue, Z., Wang, Y., Shi, Y., Gao, X., Li H., Li G., Li F., Lu L., Miao M., & Liu, X. (2023a). Multiple Mutations in SDHB and SDHC2 Subunits Confer Resistance to the Succinate Dehydrogenase Inhibitor Cyclobutrifluram in Fusarium fujikuroi. *Journal of Agricultural and Food Chemistry,* 71(8), 3694–3704. https://doi.org/10.1021/acs.jafc.2c08023

Li, Y., Tang, Y., Xue, Z., Wang, Y., Shi, Y., Gao, X., Li H., Li G., Li F., Lu L., Miao M., & Liu, X. (2023b). Resistance Risk and Resistance-Related Point Mutation in SdhB and SdhC1 of Cyclobutrifluram in Fusarium pseudograminearum. *Journal of Agricultural and Food Chemistry,* 71(4), 1886–1895. https://doi.org/10.1021/acs.jafc.2c08022

Liu, H., Lee, G., Sang, H. (2024). Exploring SDHI fungicide resistance in Botrytis cinerea through genetic transformation system and AlphaFold model-based molecular docking. *Pest Manag Sci.,* 80(11):5954-5964. doi: 10.1002/ps.8328.

MDA (2012). Fluopyram. New Active Ingredient Review. Minnesota Department of Agriculture. Available at https://web.archive.org/web/20170426233624/http://www.mda.state.mn.

Miyamoto, T., Ishii, H., & Tomita, Y. (2010). Occurrence of boscalid resistance in cucumber powdery mildew disease in Japan and the molecular characterization of iron-sulfur protein of succinate dehydrogenase of the causal fungus. *J. Gen. Plant Pathol.,* 76, 261-267.

Nishimi, S., Abe Y., Kuwahara, N., Nishimura, A., Tsukuda, S., Araki, S., Tsunematsu, K., Fukumori, Y., Ogawa,

M., Suzuki, K., & Mitani, S. (2024). Advantageous properties of a new fungicide, isofetamid. *J Pestic Sci.,* 49(2),130-134. doi: 10.1584/jpestics.D23-067.

Padmathilake, K.R.E., Parks, P.S., Gulden, R.H., Rosset, J., Zhao, L., & Fernando, W.G.D. (2022). Pydiflumetofen: An SDHI seed-applied fungicide, a potential tool for the canola-blackleg management toolbox. *Plant Pathology*, 71(9), 1992–2003. https://doi.org/10.1111/ppa.13612.

Pearce, T.L., Wilson, C.R., Gent, D.H., & Scott, J.B. (2019). Multiple mutations across the succinate dehydrogenase gene complex are associated with boscalid resistance in *Didymella tanaceti* in pyrethrum. PLoS One., 14(6): e0218569. doi: 10.1371/journal.pone.0218569.

Rehfus, A., Strobel, D., Bryson, R., & Stammler, G. (2017). Mutations in sdh genes in field isolates of *Zymoseptoria tritici* and impact on the sensitivity to various succinate dehydrogenase inhibitors. *Plant Pathology*, 67(1), 175–180. https://doi.org/10.1111/ppa.

Rehfus, A., Strobel, D., Bryson, R., & Stammler, G. (2018). Mutations in sdh genes in field isolates of Zymoseptoria tritici and impact on the sensitivity to various succinate dehydrogenase inhibitors. *Plant Pathology,* 67(1), 175–180. Available at: https://bsppjournals.onlinelibrary.wiley.com/doi/full/10.1111/ppa.12715

Samaras, A., Madesis, P., & Karaoglanidis, G.S. (2016). Detection of sdhB Gene Mutations in SDHI-Resistant Isolates of *Botrytis cinerea* Using High Resolution Melting (HRM) Analysis. *Front Microbiol.,* 7, 1815. doi: 10.3389/fmicb.2016.01815.

Scalliet, G., Boehler, M., Bowler, J., Green, P.S., Kilby, P.M., & Fonne-Pfister, R. (2010). SDHIs and fungal succinate dehydrogenase. Modern Fungicides and *Antifungal compounds V. In Proceedings 16th International Reinhardsbrunn Symposium* (pp. 171-178).

Scalliet, G., Bowler, J., Luksch, T., Kirchhofer-Allan, L., Steinhauer, D., Ward, K., Niklaus, M., Verras, A., Csukai, M., Daina, A., & Fonné-Pfister, R. (2011). Mutagenesis and Functional Studies with Succinate Dehydrogenase Inhibitors in the Wheat Pathogen *Mycosphaerella graminicola.,* PLoS one, 7, e35429

Schleker, A.S.S., Rist, M., Matera, C., Damijonaitis A., Collienne U., Matsuoka K., Habash S.S., Twelker K., Gutbrod O., Saalwächter C., Windau M., Matthiesen S., Stefanovska T., Scharwey M., Marx M.T., Geibel S., & Grundler M.W.F. (2022). Mode of action of fluopyram in plant-parasitic nematodes. Sci Rep., 12, 11954. https://doi.org/10.1038/s41598-022-15782-7

Shao, W., Wang, J., Wang, H., Wen, Z., Liu, C., Zhang, Y., Zhao, Y., & Ma, Z. (2022). Fusarium graminearum FgSdhC1 point mutation A78V confers resistance to the succinate dehydrogenase inhibitor pydiflumetofen. *Pest Manag. Sci.,* 78, 1780-1788.

Shima, Y., Ito, Y., Kaneko, S., Hatabayashi, H., Watanabe, Y., Adachi, Y. & Yabe, Y. (2009). Identification of three mutant loci conferring carboxin-resistance and development of a novel transformation system in *Aspergillus oryzae. Fungal Genetics and Biology,* 46, 67-76.

Sierotzki H., & Scalliet G. (2013). A review of current knowledge of resistance aspects for the next-generation succinate dehydrogenase inhibitor fungicides. *Phytopathology,* 103(9), 880-887.

Skinner, W., Bailey, A., Renwick A., Keon, J., Gurr, S. & Hargreaves, J. (1998). A single amino-acid substitution in the iron-sulphur protein subunit of succinate dehydrogenase determines resistance to carboxin in *Mycosphaerella graminicola. Current Genetics,* 34, 393-398.

Stammler, G., Rehfus, A., Prochnow, J., Bryson, R., & Strobel, D. (2014). New findings on the development of insensitive isolates of Pyrenophora teres towards SDHI fungicides. *Julius-Kühn-Archiv,* 447, 568.

Stammler, G., Wolf, A., Glaettli, A., & Klappach, K. (2015). Respiration Inhibitors: Complex II. In Fungicide Resistance in Plant Pathogens (pp. 105 – 117). Springer, Tokyo. https://doi.org/10.1007/978-4-431-55642-8_8

Steinhauer, D., Salat, M., Frey, R., Mosbach, A., Luksch, T., Balmer, D., and Scalliet, G. (2019). A dispensable paralog of succinate dehydrogenase subunit C mediates standing resistance towards a subclass of SDHI fungicides in *Zymoseptoria tritici*. PLoS *Pathog.* 15:e1007780.

Veloukas, T., Kalogeropoulou, S., Markoglou, D., & Karaoglanidis, G.S. (2014). Fitness and Competitive Ability of Botrytis cinerea Field Isolates with Dual Resistance to SDHI and QoI Fungicides, Associated with Several sdhB and the cytb G143A Mutations. *Phytopathology,* 104(4), 347–356. https://doi.org/10.1094/PHYTO-07-13-0208-

Veloukas, T., Leroch, M., Hahn, M., & Karaoglanidis, G.S. (2011). Detection and molecular characterization of boscalid-resistant Botrytis cinerea isolates from strawberry. *Plant Disease,* 95, 1302-130.

Von Schmeling, B., & Kulka, M. (1966). Systemic fungicidal activity of 1,4-oxathiin derivates. *Science,* 152, 659-660.

Walter, H. (2016). Fungicidal Succinate-Dehydrogenase-Inhibiting Carboxamides. In *Bioactive Carboxylic Compound Classes: Pharmaceuticals*

and Agrochemicals (pp. 405–425). Wiley. doi:10.1002/9783527693931.ch31

Yamashita, M, & Fraaije, B. (2018). Non-target site SDHI resistance is present as standing genetic variation in field populations of *Zymoseptoria tritici*. *Pest Manag Sci.,* 74(3), 672-681. doi: 10.1002/ps.4761.

Yin, Y.N., Kim, Y. K., & Xiao, C.L. (2011). Molecular characterization of boscalid resistance in field isolates of *Botrytis cinerea* from apple. *Phytopathology,* 101, 986-995

Yin, Y., Miao, J., Shao, W., Liu, X., Zhao, Y., & Ma, Z. (2023). Fungicide Resistance: Progress in Understanding Mechanism, Monitoring, and Management. *Phytopathology,* 113, 707-718. https://doi.org/10.1094/PHYTO-10-22-0370-KD

ФУНГИЦИДИ ИНХИБИТОРИ НА НАДВОРЕШНИОТ КВИНОН, ПЕРСПЕКТИВНА ГРУПА НА ПРОИЗВОДИ ЗА ЗАШТИТА НА РАСТЕНИЈАТА

Билјана Ковачевиќ[1]*, Саша Митрев[1], Емилија Арсов[1], Наталија Маркова Руждик[2], Даниела Тодевска[2], Фиданка Трајкова[3]

[1]Катедра за заштита на растенијата и животната средина, Земјоделски факултет, Универзитет Гоце Делчев, Штип, Крсте Мисирков,10А, 2000, Штип, Република Северна Македонија

[2]Катедра за растителено производство, Земјоделски факултет, Универзитет Гоце Делчев, Штип, Крсте Мисирков,10А, 2000, Штип, Република Северна Македонија

[3]Катедра за растителна биотехнологија, Земјоделски факултет, Универзитет Гоце Делчев, Штип, Крсте Мисирков,10А, 2000, Штип, Република Северна Македонија

**Контакт автор: bojana.gonovska@uklo.edu.mk*

Резиме

Ефикасното управување со растителните патогени е од суштинско значење за ублажување на појавата на популации од резистентни патогени. Значајна група на фунгициди кои играат клучна улога во интегрираните системи за управување со болестите кај растенијата, а, меѓу другото, и поради нивната ниска еколошка токсичност, се инхибиторите на сукцинат дехидрогеназа, кои делуваат на тој начин што се сврзуваат за митохондријалниот комплекс II од респираторниот систем кај габите. За разлика од првата генерација на инхибитори на сукцинат дехидрогеназа (на пр., карбоксин и оксикарбоксин), кои покажуваат висока ефикасност кон патогените од класата на базидиомицети, поновите соединенија од оваа група на фунгициди (на пр., циклобутрифлурам, фураметпир и инпирфлуксам) покажуваат широк спектар на активност кон различни видови на габи. Сепак, нивната несоодветна употреба може да го фаворизира развојот на резистентни генотипови, што ја намалува нивната ефикасност. Овој прегледен труд дава увид во молекуларните механизми на кои се должи отпорноста на габите кон SDHI, како и некои други фактори што влијаат на појавата на отпорност. Исто така, даден е увид во стратегиите за ефикасна употреба на новоразвиените SDHI молекули и предложени се клучните насоки на кои треба да се темелат идните истражувања за справување со резистентноста кон оваа група на фунгициди.

Клучни зборови: *инхибитори на сукцинат дехидрогеназа, резистентност, заштита на растенијата, механизам на делување, фунгицидно дејство.*