Mode of Action of Fungicides

FRAC classification on mode of action 2014 (www.frac.info)

A: Nucleic Acid Synthesis

A1: RNA polymerase I

4: PA-fungicides (PhenylAmides)

acylalanines: benalaxyl, benalaxyl-M, furalaxyl, metalaxyl, metalaxyl-M

butyrolactones: ofurace

oxazolidinones: oxadixyl

A2: adenosin-deaminase

8: hydroxy (2-amino)-pyrimidines

bupirimate, dimethirimol, ethirimol

A3: DNA / RNA synthesis (prop.)

32: heteroaromatics

isoxazoles: hymexazole

isothiazolones: octhilinone

A4: DNA topoisomerase type II (gyrase)

31: carboxylic acids

oxolinic acid (bactericide)

B: Mitosis and Cell Division

B1: ▷ ß-tubulin assembly in mitosis

1: MBC fungicides (= Methyl Benzimidazole Carbamates)

benzimidazoles: benomyl, fuberidazole, carbendazim, thiabendazole

thiophanates: thiophanate, thiophanate-methyl

B2: ▷ ß-tubulin assembly in mitosis*

10 N-phenyl carbamates

diethofencarb

* negative cross-resistance to B1

B3: ▷ß-tubulin assembly in mitosis

22 benzamides and thiazole carboxamides

toluamide: zoxamide

ethylamino-thiazole carboxamide: ethaboxam

B4: cell division (prop.)

20 phenylureas

pencycuron

B5: delocalisation of spectrin-like proteins

43 benzamides

pyridinylmethyl-benzamide: fluopicolide

C: Respiration

C2: inhibition of complex II: succinate-dehydrogenase

7 SDHI (Succinate DeHydrogenase Inhibitors)

pyrazole -4-carboxamides: fluxapyroxad, furametpyr, penflufen, penthiopyrad

thiazole carboxamides: thifluzamide

phenyl-oxo-ethyl thiophene amide: isofetamid

pyridinyl-ethyl benzamides: fluopyram

pyridine carboxamides: boscalid

oxathiin carboxamides: carboxin, oxycarboxin

furan carboxamides: fenfuram

bixafen, isopyrazam, sedaxane, benzovindiflupyr

phenyl-benzamides: flutolanil, mepronil, benodanil

C: Respiration

C1: inhibition of complex I NADH Oxido-reductase

39 pyrimidinamines pyrazole-MET1

pyrimidinamine: diflumetorim

pyrazole -5-carboxamide: tolfenpyrad

C4: inhibition of complex III

▷ cytochrome bc1(ubiquinone reductase) at Qi site

▷# 21 Qil fungicides (Quinone inside Inhibitors)

cyano-imidazole: cyazofamid

sulfamoyl-triazole: amisulbrom

C8: inhibition of complex III

▷ cytochrome bc1(ubiquinone reductase) at Qo site stigmatellin binding sub site)

45 QoSI-fungicide (stigmatellin binding type)

triazolo-pyrimidylamine: ametoctradin

C6: inhibitors of oxidative phosphorylation, ATP synthase

30 organo tins

fentin acetate, fentin chloride, fentin hydroxide

C3: inhibition of complex III cytochrome bc1 (ubiquinol oxidase) at Qo site (*cyt b gene*)

11 QoI fungicides (Quinone outside Inhibitors)

methoxy-acrylates: azoxystrobin, picoxystrobin, enoxastrobin, pyraoxystrobin

methoxy-acetamides: mandestrobin

oximino-acetamides: orysastrobin, dimoxystrobin, metominostrobin, fenaminstrobin

methoxy-carbamates: pyraclostrobin, pyrametostrobin, triclopyricarb

oximino-acetates: kresoxim-methyl, trifloxystrobin

oxazolidine-diones: famoxadone

imidazolinones: fenamidone

benzy-l-carbamates: pyribencarb

dihydro-dioxazines: fluoxastrobin

flufenoxystrobin, coumoxystrobin

C7: ATP production (prop.)

38 thiophene-carboxamides

silthiofam

C5: uncouplers of oxidative phosphorylation

29

2,6-dinitro-aniline: fluazinam

dinitrophenyl crotonates: meptyl dinocap, binapacryl

D: Amino Acid and Protein Synthesis

D1: methionine biosynthesis (cgs gene) (prop.)

9 Anilino-Pyrimidines (AP fungicides)

cyprodinil, mepanipyrim, pyrimethanil

D2: protein synthesis

23 enopyranuronic acid

blasticidin-S

D3: protein synthesis

24 hexopyranosyl antibiotics

kasugamycin

D4: protein synthesis

25 glucopyranosyl antibiotics

streptomycin (bactericide)

D5: protein synthesis

41 tetracycline antibiotics

oxytetracycline (bactericide)

E: Signal Transduction

E1: Signal transduction (mechanism unknown)

#13 azanaphthalenes

aryloxyquinoline: quinoxyfen

quinazolinone: proquinazid

E2: Osmotic signal transduction ▷ MAP / histidine- kinase (os-2, HOG1)

12 phenylpyrroles (PP- fungicides)

fenpiclonil, fludioxonil

E3: Osmotic signal transduction ▷ MAP / histidine kinase (os-1, Daf1)

2 dicarboximides

iprodione, chlozolinate, vinclozolin, procymidone

F: Lipid Synthesis and Membrane Integrity

F2: phospholipid biosynthesis ▷ methyltransferase

6 phosphorothiolates & dithiolanes

phosphorothiolates: pyrazophos, iprobenfos, edifenphos

dithiolanes: iso-prothiolane

F3: lipid peroxidation (prop.)

14 aromatic hydrocarbons & heteroaromatics

aromatic hydrocarbons: tecnazene (TCNB), dicloran, quintozene (PCNB), biphenyl, tolclofos-methyl, chloroneb

1,2,4-thiadiazole: etridiazole

F4: cell membrane permeability, fatty acids (prop.)

28 carbamates

propamocarb, iodocarb, prothiocarb

F6: microbial disrupters of pathogen cell membranes

44 Microbial (*Bacillus* sp.)

Bacillus sp. and the fungicidal lipopeptides produced

Bacillus amyloliquefaciens (synonym *B. subtilis*) strains: QST 713, FZB24, MBI600, D747

F7: cell membrane disruption (prop.)

46 *plant extract.*

Melaleuca alternifolia (Tea Tree Extract)

I: Melanin Synthesis in Cell Wall

I1: reductase in melanin biosynthesis

16.1 Melanin Biosynthesis Inhibitors Reductase (MBI-R)

isobenzofuranone: fthalide

pyrroloquinolione: pyroquilon

triazolobenzothiazole: tricyclazole

I2: dehydratase in melanin biosynthesis

16.2 Melanin Biosynthesis Inhibitors Dehydratase (MBI-D)

cyclopropane carboxamide: carpropamid

carboxamide: diclocymet

propionamide: fenoxanil

G: Sterol Biosynthesis in membranes

G1: C14-demethylase in sterol biosynthesis (*erg11/cyp51*)

3 DMI-fungicides (DeMethylation Inhibitors) (SBI: Class I)

triazoles: etaconazole, azaconazole, ipconazole, fenbuconazole, tebuconazole, bitertanol, metconazole, fluquinconazole, tetraconazole, bromuconazole, mycobutanil, flusilazole, triadimefon, cyproconazole, penconazole, triadimenol, flutriafol, difenoconazole, propiconazole, hexaconazole, triticonazole, diniconazole, simeconazole, imibenconazole, epoxiconazole

triazolinthione: prothioconazole

piperazines: triforine

pyridines: pyrifenox, pyrisoxazole

pyrimidines: nuarimol, fenarimol

imidazoles: imazalil, pefurazoate, triflumizole, oxpoconazole, prochloraz

G2:Δ14-Reductase and Δ8→Δ7-isomerase in sterol biosynthesis (*erg2, erg 24*)

5 Amines("Morpholines") (SBI: Class II)

morpholines: aldimorph, n = 10 to 13, n = 12: ~ 70%, tridemorph, fenpropimorph, dodemorph

piperidines: fenpropidin, piperalin

spiroketal-amines: spiroxamine

G3:3-Keto reductase in C4-de-methylation (*erg27*)

17 (SBI :Class III)

hydroxyanilides: fenhexamid

amino-pyrazolinones: fenpyrazamine

G4: Squalene epoxidase in sterol biosynthesis (*erg1*)

18 (SBI class IV)

allylamines: naftifine (antimycotic), terbinafine (antimycotic)

thiocarbamates: pyributicarb (herbicide)

H:Cell Wall Biosynthesis

H3: trehalase and inositol biosynthesis

26 glucopyranosyl antibiotic

validamycin

H4: chitin synthase

19 polyoxins

Peptidyl pyrimidine nucleoside: polyoxin B

H5: cellulose synthase

40 Carboxylic Acid Amides (CAA fungicides)

cinnamic acid amides: dimethomorph, flumorph, pyrimorph

mandelic acid amides: mandipropamid

valinamide carbamates: iprovalicarb, benthiavalicarb, valifenalate

P: Host Plant Defence Induction

P1: salicylic pathway

benzothiodiazole BTH: acibenzolar-S-methyl

P2:

benzothiazole: probenazole

P3:

thiadiazole carboxamide: isotianil, tiadinil

P4:

polysaccharide: laminarin

P5:

plant extract: *Reynoutria sachalinensis* (Giant Knotweed Extract)

M: Multi Site Action

#M1/2 inorganics: copper preparations, sulphur

#M3 dithiocarbamates & relatives: febram, mancozeb, metiram, propineb, thiram, zineb, maneb, ziram

#M8 triazines: anilazine

#M9 anthraquinones: dithianon

#M5 chloronitriles: chlorothalonil

#M4 phthalimides: captan, captafol, folpet

#M6 sulphamides: dichlofluanid, tolylfluanid

#M7 guanidines: mixture of iminoctadine and other polyamines, guazatine, iminoctadine

#M10 quinoxalines: chinomethionat

#M11 maleimides: fluoroimide

Unknown Mode of Action

cyanoacetamide-oxime: # 27 cymoxanil

ethyl-phosphonates: # 33 fosetyl-al

phosphorous acid: H_3PO_3, # 33 phosphorous acid

phthalamic acid: # 34 teclofthalam

phenyl acetamides: # U6 cyflufenamid

cyano-methylene thiazolidine: # U13 flutianil

pyrimidinone-hydrazones: # U14 ferimzone

Piperidinyl- thiazole isoxazoline: # U15 oxathiapiprolin

benzotriazines: # 35 triazoxide

benzene-sulfonamides: # 36 flusulfamide

pyridazinones: # 37 diclomezine

thiocarbamates: # 42 methasulfocarb

guanidines: # U12 dodine

arylphenylketones: # U8 metrafenone, # U8 pyriofenone

4-quinolyl acetate: # U16 tebufloquin

•Temporary status; information on mode of action and +/ or resistance risk is still uncertain

NC : Not Classified

Mineral oils, organic oils, potassium bicarbonate, material of biological origin

Mode of action of fungicides based on the FRAC fungicide list (published at www.frac.info/publications)

The groupings can change when new results become known. Yellow zones represent accepted mode of action groups or in cases where resistance is known, cross resistance groups. In spite of this general classification, cases of incomplete or even lacking cross resistance are known within some groups with some pathogens.

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Legend:

C: Respiration — mode of action group

C2: inhibition of complex II: ▷ succinate-dehydrogenase — sub-group

7 SDHI (Succinate dehydrogenase inhibitors) — ▷ target site of action (where known) or putative target site (=prop.)

FRAC code no. (#) and group name

chemical (sub-) group: thiazole carboxamides

FRAC FUNGICIDE RESISTANCE ACTION COMMITTEE

CropLife INTERNATIONAL