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, carbendazim, thiabendazole
tuberidazole
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: furametpyr, penthiopyrad, penflufen, fluxapyroxad
bixafen, isopyrazam, sedaxane, benzovindiflupyr
thiazole carboxamides: thifluzamide
phenyl-oxo-ethyl thiophene amide: isofetamid
pyridinyl-ethyl benzamides: fluopyram
pyridine carboxamides: boscalid
oxathiin carboxamides: carboxin, oxycarboxin
furan carboxamides: fenfuram
phenyl-benzamides: flutolanil, mepronil, benodanil

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, benzy-l-carbamates, pyribencarb
oxazolidine-diones: famoxadone
imidazolinones: fenamidone
dihydro-dioxazines: fluoxastrobin
fluoxastrobin, fluoxastrobin, 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, vinclozolin, procymidone, chlozolinate

F: Lipid Synthesis and Membrane Integrity

F2: phospholipid biosynthesis ▷ methyltransferase
6 phosphorothiolates & dithiolanes

phosphorothiolates: pyrazophos, iprobenfos, edifenphos
dithiolanes: isoprothiolane

F3: lipid peroxidation (prop.)
14 aromatic hydrocarbons & heteroaromatics

aromatic hydrocarbons: tecnazene (TCNB), dicloran, quintozene (PCNB), biphenyl, tolclofos-methyl, chloroneb
etridiazole
1,2,4-thiadiazole

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: azaconazole, etaconazole, ipconazole, fenbuconazole, tebuconazole, bitertanol, metconazole, fluquinconazole, tetraconazole, bromuconazole, myclobutanil, flusilazole, triadimefon, cyproconazole, penconazole, triadimenol, flutriafol, propiconazole, difenoconazole, hexaconazole, triticonazole, diniconazole, simeconazole, mibenconazole, prothioconazole, epoxiconazole
piperazines: triforine
pyridines: pyrifenox, pyrisoxazole
pyrimidines: nuarimol, fenarimol
imidazoles: imazalil, triflumizole, pefurazoate, oxpoconazole, prochloraz
triazolinthione

G2:Δ14-Reductase and Δ8→ Δ7-isomerase in sterol biosynthesis (*erg2, erg 24*)
5 Amines("Morpholines") (SBI: Class II)

morpholines: aldmorph, fenpropimorph, tridemorph, 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: terbinafine (antimycotic), naftifine (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, valifenalate, benthiavalicarb

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

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)

NC : Not Classified

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

M: Multi Site Action

#M1/2 inorganics: Cu copper preparations, S sulphur
#M3 dithiocarbamates & relatives: febram, mancozeb, metiram, maneb, propineb, thiram, ziram, zineb
#M8 triazines: anilazine
#M4 phthalimides: captan, captafol, folpet
#M6 sulphamides: dichlofluanid, tolylfluanid
#M9 anthraquinones: dithianon
#M5 chloronitriles: chlorothalonil
#M10 quinoxalines: chinomethionat
#M7 guanidines: mixture of iminoctadine and other polyamines, iminoctadine, guazatine
#M11 maleimides: fluoroimide

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: — sub-group
▷ succinate-dehydrogenase — ▷ target site of action (where known) or putative target site (=prop.)
7 SDHI (Succinate dehydrogenase Inhibitors) — FRAC code no. (#) and group name
thiazole carboxamides — chemical (sub-) group

FRAC FUNGICIDE RESISTANCE ACTION COMMITTEE

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