Mode of Action of Fungicides

FRAC classification on mode of action 2017 (www.frac.info)

A: Nucleic Acid Synthesis

A1: RNA polymerase I
4: PA-fungicides (PhenylAmides)

benalaxyl, metalaxyl, furalaxyl, benalaxyl-M, metalaxyl-M — acylalanines

ofurace — butyrolactones

oxadixyl — oxazolidinones

A2: adenosin-deaminase
8: hydroxy (2-amino)-pyrimidines

bupirimate, dimethirimol, ethirimol

A3: DNA / RNA synthesis (prop.)
32: heteroaromatics

hymexazole — isoxazoles

octhilinone — isothiazolones

A4: DNA topoisomerase type II (gyrase)
31: carboxylic acids

oxolinic acid (bactericide)

B: Cytoskeleton and Motor Proteins

B1: ▹ ß-tubulin assembly in mitosis
1: MBC fungicides
(= Methyl Benzimidazole Carbamates)

benomyl, fuberidazole, carbendazim — benzimidazoles

thiabendazole, thiophanate, thiophanate-methyl — thiophanates

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

B6: actin/myosin/ fimbrin function e.g. in vesicle trafficking
47 cyanoacrylates

aminocyanoacrylates: phenamacril

C: Respiration

C2: inhibition of complex II: succinate-dehydrogenase
7 SDHI (Succinate DeHydrogenase Inhibitors)

fluxapyroxad, furametpyr, penflufen — pyrazole - 4 - carboxamides

penthiopyrad, bixafen, isopyrazam, sedaxane — Pyridinyl - ethyl - benzamides

benzovindiflupyr

Thiazole - carboxamides: thifluzamide

phenyl-oxo-ethyl thiophene amide: isofetamid

fluopyram — N-methoxy-(phenyl-ethyl)-pyrazole-carboxamides

pydiflumetofen — pyrazine - carboxamides

pyraziflumid, benodanil

Pyridine - carboxamides: boscalid

Oxathiin - carboxamides: carboxin, oxycarboxin

fenfuram — furan - carboxamides

mepronil, flutolanil — phenyl-benzamides

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, coumoxystrobin

oximino-acetamides: orysastrobin, dimoxystrobin, metominostrobin, fenaminstrobin

methoxy-carbamates: pyraclostrobin, pyrametostrobin, triclopyricarb, benzyl-carbamates

oximino-acetates: kresoxim-methyl, trifloxystrobin, pyribencarb

oxazolidine-diones: famoxadone

imidazolinones: fenamidone

dihydro-dioxazines: fluoxastrobin

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, dimethachlone

F: Lipid Synthesis or Transport / Membrane Integrity or Function

F2: phospholipid biosynthesis ▹ methyltransferase
6 phosphorothiolates & dithiolanes

phosphorothiolates: pyrazophos, iprobenfos, edifenphos

dithiolanes: iso-prothiolane

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

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

etridiazole — 1,2,4-thiadiazole

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

prothiocarb, propamocarb, iodocarb

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)**

Plant oils (mixtures) eugenol, geraniol thymol

F8: ergosterol binding
48 polyene

natamycin (pimaricin)

F9: lipid homeostasis and transfer/storage
49 OSBPI
Oxysterol binding protein homologue inhibition

oxathiapiprolin — piperidinyl-thiazole - isoxazoline

I: Melanin Synthesis in Cell Wall

I1: reductase in melanin biosynthesis
16.1 Melanin Biosynthesis Inhibitors: Reductase (MBI-R)

isobenzo-furanone: fthalide

pyrrolo-quinolione: pyroquilon

triazolobenzo-thiazole: tricyclazole

I2: dehydratase in melanin biosynthesis
16.2 Melanin Biosynthesis Inhibitors: Dehydratase (MBI-D)

carboxamide: diclocymet

cyclopropane carboxamide: carpropamid

propionamide: fenoxanil

I3: polyketide synthase in melanin biosynthesis
16.3 Melanin Biosynthesis Inhibitors: Polyketide synthase (MBI-P)

trifluoroethyl-carbamate: tolprocarb

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, myclobutanil, 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, triflumizole, pefurazoate, oxpoconazole, prochloraz

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

morpholines: aldimorph, fenpropimorph, tridemorph (n = 10 to 13, n = 12 - : 70%), 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

H4: chitin synthase
19 Polyoxins

Polyoxin B — peptidyl pyrimidine nucleoside

H5: cellulose synthase
40 Carboxylic Acid Amides
(CAA fungicides)

cinnamic acid amides: dimethomorph, flumorph, pyrimorph

mandelic acid amides: mandipropamid

valinamide carbamates: iprovalicarb, valifenalate, benthiavalicarb

P: Host Plant Defence Induction

P01: salicylic pathway
benzothiodiazole BTH: acibenzolar-S-methyl

P02: benzothiazole
probenazole

P03: thiadiazole carboxamide
isotianil, tiadinil

P04: polysaccharide
laminarin

P05: plant extract
Reynoutria sachalinensis
(Giant Knotweed Extract)

P06: *Bacillus cereus* group
Bacillus mycoides
(Isolate J)

BM : Biologicals with Multiple Modes of Action

BM01: polypeptide lectin
Extract from the cotyledons of lupine plantlets
(BLAD)

BM02: *Trichoderma* spp. metabolites
Trichoderma atroviride
(strain SC1)

M: Chemicals with Multi-Site Activity

#M01/02 inorganics: copper preparations (Cu), sulphur (S)

#M03 dithiocarbamates & relatives: febram, metiram, mancozeb, propineb, thiram, zineb, zinc thiazole, maneb, ziram

#M04 phthalimides: captan, captafol, folpet

#M05 chloronitriles: dithianon, chlorothalonil

#M06 sulphamides: dichlofluanid, tolylfluanid

#M07 guanidines: mixture of iminoctadine and other polyamines, guazatine, iminoctadine

#M08 triazines: anilazine

#M09 anthraquinones: dithianon

#M10 quinoxalines: chinomethionat

#M11 maleimides: fluoroimide

Unknown Mode of Action

\# 27 cymoxanil — cyanoacetamide-oxime

\# 33 fosetyl-al — ethyl-phosphonates

H_3PO_3 — \# 33 phosphorous acid — phosphorous acid

\# 34 tecloftalam — phthalamic acid

\# U6 cyflufenamid — phenyl acetamides

\# U13 flutianil — cyano-methylene thiazolidine

\# U14 ferimzone — pyrimidinone-hydrazones

\# U16 tebufloquin — 4-quinolyl acetate

\# 35 triazoxide — benzotriazines

\# 36 flusulfamide — benzene-sulfonamides

\# 37 diclomezine — pyridazinones

\# 42 methasulfocarb — thiocarbamates

\# U12 dodine — guanidines

\# U08 meptaldinone — arylphenyl ketones

\# U08 pyriofenone

\# U17 picarbutrazox — tetrazolyloxime

\# U18 validamycin — glucopyranosyl antibiotic

•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
C2: inhibition of complex II:
▹ succinate-dehydrogenase
7 SDHI (Succinate dehydrogenase inhibitors)

- mode of action group
- sub-group
- ▹ 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

FRAC Mode of Action Poster ©
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