FRAC Classification of Fungicides

Fungal control agents by cross resistance pattern and mode of action 2019 (www.frac.info)

A: Nucleic Acids Metabolism

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)

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

B4: cell division (unknown site)
20 phenylureas

pencycuron

B3: ▹ß-tubulin assembly in mitosis
22 benzamides and thiazole carboxamides

toluamide: zoxamide

ethylamino-thiazole carboxamide: ethaboxam

B5: delocalisation of spectrin-like proteins
43 benzamides

pyridinylmethyl-benzamide: fluopicolide, fluopimomide

B6: actin/myosin/fimbrin function
47 cyanoacrylates
50 aryl-phenyl-ketones

aminocyanoacrylates: phenamacril

benzophenone: metrafenone

benzoylpyridine: pyriofenone

C: Respiration

C1: complex I NADH Oxido-reductase
39 pyrimidinamines,pyrazole-MET1, quinazoline

pyrimidinamine: diflumetorim

pyrazole -5-carboxamide: tolfenpyrad

quinazoline: fenazaquin

C4: complex III cytochrome bc1(ubiquinone reductase) at Qi site
21 Qil fungicides (Quinone inside Inhibitors)

cyano-imidazole: cyazofamid

sulfamoyl-triazole: amisulbrom

picolinamide: fenpicoxamid

C8: inhibition of complex III cytochrome bc1(ubiquinone reductase) at Qo site stigmatellin binding sub site)
45 QoSI-fungicide (stigmatellin binding

triazolo-pyrimidylamine: ametoctradin

C6: inhibitors of oxidative phosphorylation, ATP synthase
30 organo tins

fentin acetate, fentin chloride, fentin hydroxide

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

fluxapyroxad, furametpyr, penflufen — pyrazole - 4 - carboxamides

phenyl-oxo-ethyl thiophene amide: penthiopyrad

bixafen, sedaxane, isopyrazam, benzovindiflupyr, fluindapyr, inpyrfluxam, isoflucypram

thiazole - carboxamides: thifluzamide, isofetamid

pyridine - carboxamides: boscalid

oxathiin - carboxamides: carboxin, oxycarboxin

pyridinyl - ethyl - benzamides: fluopyram

pydiflumetofen

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

N-cyclopropyl-N-Benzyl-pyrazole-carboxamides

pyraziflumid

pyrazine - carboxamides: benodanil, mepronil, flutolanil

furan - carboxamides: fenfuram

phenyl-benzamides

C3: 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, flufenoxystrobin, coumoxystrobin

oximino-acetamides: orysastrobin, dimoxystrobin, metominostrobin, fenaminstrobin

methoxy-carbamates: pyraclostrobin, pyrametostrobin, triclopyricarb, pyribencarb

oximino-acetates: kresoxim-methyl, trifloxystrobin

benzyl-carbamates

oxazolidine-diones: famoxadone

imidazolinones: fenamidone

dihydro-dioxazines: fluoxastrobin

C7: ATP transport (proposed)
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) (proposed)
9 Anilino-Pyrimidines (AP fungicides)

cyprodinil, mepanipyrim, pyrimethanil

D2: protein synthesis (ribosome, termination step)
23 enopyranuronic acid

blasticidin-S

D3: protein synthesis (ribosome, initiation step)
24 hexopyranosyl antibiotics

kasugamycin

D4: protein synthesis (ribosome, initiation step)
25 glucopyranosyl antibiotics

streptomycin (bactericide)

D5: protein synthesis (ribosome, elongation step)
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: cell 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
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, propiconazole, difenoconazole, hexaconazole, triticonazole, diniconazole, simeconazole, mefentrifluconazole, imibenconazole, epoxiconazole, prothioconazole — triazolinthione

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)

aldimorph, tridemorph, fenpropimorph, dodemorph — morpholines

piperidines: fenpropidin, piperalin

spiroketal-amines: spiroxamine

G3:3-keto reductase in C4-de-methylation (*erg27*)
17 (KRI fungicides KetoReductase Inhibitors) (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)

dimethomorph, flumorph, pyrimorph — cinnamic acid amides

mandipropamid — mandelic acid amides

iprovalicarb, valifenalate, benthiavalicarb — valinamide carbamates

P: Host Plant Defence Induction

P1: salicylate related
P01 benzothiadiazole BTH

acibenzolar-S-methyl

P2: salicylate related
#P02 benzothiazole

probenazole

P3:salicylate related
#P03 thiadiazole carboxamide

isotianil, tiadinil

P4:polysaccharide elicitors
#P04 polysaccharide

laminarin

P5:anthraquinone elicitors
#P05 plant extract

Reynoutria sachalinensis (Giant Knotweed Extract)

P6:microbial elicitors
#P06

Bacillus mycoides (Isolate J)

Bacterial *Bacillus* spp.

Cell walls of *Saccharomyces cerevisiae* Strain LAS117

Fungal *Saccharomyces* spp.

P7:phosphonates
#P07 phosphonates

fosetyl-al, ethyl-phosphonates

H_2PO_3 phosphorous acid

Phosphorous acid

NC : Not Classified

Mineral oils, organic oils, inorganic salts material of biological origin

M: Chemicals with Multi-Site Activity

#M01 inorganic (electrophiles): copper preparations (Cu)

#M02 inorganic (electrophiles): sulphur (S)

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

#M04 phthalimides (electrophiles): captan, captafol, folpet

#M05 chloronitriles (unspecified mechanism): chlorothalonil

#M06 sulphamides (electrophiles): dichlofluanid, tolylfluanid

#M07 bis-guanidines (membrane disruptors, detergents): guazatine (mixture of iminoctadine and other polyamines), iminoctadine

#M08 triazines (unspecified mechanism): anilazine

#M09 anthraquinones (electrophiles): dithianon

#M10 quinoxalines (electrophiles): chinomethionat

#M11 maleimides (electrophiles): fluoroimide

#M12 thiocarbamates (electrophiles): methasulfocarb

Unknown Mode of Action

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

#27 cyanoacetamide-oxime: cymoxanil

#34 phthalamic acid: tecloftalam

#35 benzotriazines: triazoxide

#36 benzene-sulfonamides: flusulfamide

37 pyridazinones: diclomezine

#U06 phenyl acetamides: cyflufenamid

#U13 cyano-methylene thiazolidine: flutianil

#U14 pyrimidinone-hydrazones: ferimzone

#U16 4-quinolyl acetate: tebufloquin

#U17 tetrazolyloxime: picarbutrazox

#U18 glucopyranosyl antibiotic: validamycin

#U12 guanidines: dodine

BM : Biologicals with Multiple Modes of Action

BM 02:microbial (living microbes or extract, metabolites)

Trichoderma atroviride (strain SC1), *Trichoderma atroviride* (strain I-1237), *Trichoderma atroviride* (strain LU132), *Trichoderma atroviride* (strain T34) — *Fungal Trichoderma* spp.

Streptomyces griseovirides (strain K61) — *Bacterial Streptomyces* spp.

Gliocladium catenulatum (strain J1446) — *Fungal Gliocladium* spp.

BM 01:plant extract

polypeptide lectin

Extract from the cotyledons of lupine plantlets (BLAD)

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

CropLife INTERNATIONAL