FRAC Classification of Fungicides

FRAC FUNGICIDE RESISTANCE ACTION COMMITTEE

Fungal control agents by cross resistance pattern and mode of action 2024 (www.frac.info)

A: Nucleic Acids Metabolism

A1: RNA polymerase I
4: PA-fungicides (Phenyl Amides)

benalaxyl, benalaxyl-M, furalaxyl, metalaxyl, Subdue, metalaxyl-M, ofurace, oxadixyl

acylalanines; butyrolactones; oxazolidinones — Group 4

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

bupirimate, Nimrod, dimethirimol, ethirimol — Group 8

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

hymexazole, isoxazoles, octhilinone, isothiazolones — Group 32

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

oxolinic acid (bactericide) — Group 31

A5: inhibition of dihydroorotate dehydrogenase within *de novo* pyrimidine biosynthesis
52: DHODHI-fungicides

ipflufenoquin, phenyl-propanol, quinofumelin, dihydroisoquinoline — Group 52

B: Cytoskeleton and Motor Proteins

B1: tubulin polymerization
1: MBC fungicides (= Methyl Benzimidazole Carbamates)

benzimidazoles, fuberidazole, benomyl, thiabendazole, carbendazim, thiophanate-methyl, thiophanate, thiophanates — Group 1

B2: tubulin polymerization*
10 N-phenyl carbamates

diethofencarb

*negative cross-resistance to B1 — Group 10

B4: cell division (unknown site)
20 phenylureas

pencycuron, phenylurea — Group 20

B3: tubulin polymerization
22 benzamides and thiazole carboxamides

zoxamide, toluamide, ethaboxam, ethylamino-thiazole carboxamide — Group 22

B5: delocalisation of spectrin-like proteins
43 benzamides

fluopimomide, pyridinylmethyl benzamides, fluopicolide — Group 43

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

phenamacril, aminocyanoacrylates, pyriofenone, benzoylpyridine, metrafenone, benzophenone — Group 47, Group 50

B7: tubulin dynamics modulator
53 pyridazine

pyridachlometyl, pyridazine — Group 53

C: Respiration

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

diflumetorim, tolfenpyrad, fenazaquin; pyrimidinamine, pyrazole-5-carboxamide, quinazoline — Group 39

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

fluxapyroxad, Sercadis, furametpyr, penflufen, pyrazole - 4 - carboxamides, bixafen, sedaxane, fluindapyr, phenyl-oxo-ethyl thiophene amide, penthiopyrad, isopyrazam, Reflect, inpyrfluxam, thiazole - carboxamides, benzovindiflupyr, cyclobutrifluram, isofetamid, pyridinyl – ethyl - benzamides, pyrazine - carboxamides, isoflucypram, phenyl-cyclobutyl pyridineamide, benodanil, thifluzamide, fluopyram, N-cyclopropyl-N-Benzyl-pyrazole-carboxamides, pyridine - carboxamides, pyraziflumid, oxycarboxin, oxathiin - carboxamides, carboxin, fenfuram, furan-carboxamides, pydiflumetofen, N-methoxy-(phenyl-ethyl)-pyrazole-carboxamides, phenyl-benzamides, mepronil, boscalid, Signum +, flutolanil — Group 7

C3: complex III cytochrome bc1 (ubiquinol oxidase) at Qo site (*cyt b gene*)
11 QoI fungicides (Quinone outside Inhibitors)

coumoxystrobin, enoxastrobin, picoxystrobin, pyraoxystrobin, methoxy-acrylates, azoxystrobin, Amistar, flufenoxystrobin, Signum +, kresoxim-methyl, Stroby, oximino-acetates, trifloxystrobin, Nativo +, dihydro-dioxazines, fluoxastrobin, mandestrobin, methoxy-acetamides, famoxadone, oxazolidine-diones, oximino-acetamides, fenaminstrobin, orysastrobin, metominostrobin, dimoxystrobin, fenamidone, imidazolinones, methoxy-carbamates, pyrametostrobin, pyraclostrobin, triclopyricarb, pyribencarb, benzyl-carbamates — Group 11, Group 11A

C4: complex III
cytochrome bc1(ubiquinone reductase) at Qi site
21 QiI fungicides (Quinone Inside Inhibitors) — Group 21

cyano-imidazole, cyazofamid, sulfamoyl-triazole, amisulbrom, picolinamide, fenpicoxamid, florylpicoxamid

C5: uncouplers of oxidative Phosphorylation
29

meptyl dinocap, dinitrophenyl crotonates, binapacryl, 2,6-dinitro-aniline, fluazinam — Group 29

C6: inhibitors of oxidative phosphorylation ATP synthase
30 organo tins

fentin acetate, fentin chloride, fentin hydroxide — Group 30

C7: ATP transport (proposed)
38 thiophene- carboxamides

silthiofam — Group 38

C8: inhibition of complex III
cytochrome bc1 (ubiquinone reductase) at Qi and Qo sites (stigmatellin binding mode)
45 QioSI-fungicide (Quinone inside and outside inhibitor, stigmatellin binding mode)

ametoctradin; triazolo-pyrimidylamine — Group 45

D: Amino Acid and Protein Synthesis

D1: methionine biosynthesis (cgs gene) (proposed)
9 Anilino-Pyrimidines (AP fungicides)

cyprodinil, pyrimethanil, mepanipyrim, Switch +, Frupica — Group 9

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

blasticidin-S — Group 23

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

kasugamycin — Group 24

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

streptomycin (bactericide) — Group 25

D5: protein synthesis (ribosome, elongation step)
41 tetracycline antibiotics

oxytetracycline (bactericide) — Group 41

D6: leucyl-tRNA synthetase (LeuRS)
54 benzoxaboroles

tavaborole — Group 54

E: Signal Transduction

E1: signal transduction (mechanism unknown)
#13 azanaphthalenes

aryloxyquinoline, quinoxyfen, quinazolinone, proquinazid — Group 13

E2: osmotic signal transduction ▷ MAP / histidine- kinase (os-2, HOG1)
12 phenylpyrroles (PP- fungicides)

fenpiclonil, fludioxonil — Switch +, Group 12

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

iprodione, chlozolinate, vinclozolin, procymidone, dimethachlone — Group 2

F: Lipid Synthesis or Transport / Membrane Integrity or Function

F2: phospholipid biosynthesis ▷ methyltransferase
6 phosphorothiolates & dithiolanes

phosphorothiolates: pyrazophos, iprobenfos, edifenphos; dithiolanes: iso-prothiolane — Group 6

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

aromatic hydrocarbons: dicloran, tecnazene (TCNB), quintozene (PCNB), biphenyl, tolclofos-methyl, chloroneb; 1,2,4-thiadiazole: etridiazole — Group 14

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

propamocarb, prothiocarb, iodocarb — Group 28

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

oxathiapiprolin, fluoxapiproline; Piperidinyl thiazole - isoxazoline — Group 49

F8: ergosterol binding
48 polyene

natamycin (pimaricin) — Group 48

F10: interaction with lipid fraction of cell membrane, with multiple effects on cell membrane integrity
51 protein fragment

Polypeptide ASFBIOF01-02; polypeptide — Group 51

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 — Group 16.1

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

carboxamide: diclocymet; cyclopropane carboxamide: carpropamid; propionamide: fenoxanil — Group 16.2

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

tolprocarb; trifluoroethyl-carbamate — Group 16.3

G: Sterol Biosynthesis in Membranes

G1: C14-demethylase in sterol biosynthesis (*erg11/cyp51*)
3 DMI-fungicides (DeMethylation Inhibitors) (SBI : Class I)

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

piperazines: triforine

pyridines: pyrifenox, pyrisoxazole

pyrimidines: nuarimol, fenarimol

imidazoles: imazalil, pefurazoate, trifumizole, oxpoconazole, prochloraz, prothioconazole

triazolinthione

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Group 3

G2: Δ^{14}-reductase and $\Delta^{8} \rightarrow \Delta^{7}$-isomerase in sterol biosynthesis (*erg2, erg 24*)
5 Amines("Morpholines") (SBI : Class II)

piperidines: fenpropidin, piperalin

morpholines: aldimorph, fenpropimorph, tridemorph, dodemorph

spiroketal-amines: spiroxamine — Group 5

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

hydroxyanilides: fenhexamid

amino-pyrazolinones: fenpyrazamine — Group 17

G4: squalene epoxidase in sterol biosynthesis (*erg1*)
18 (SBI : Class IV)

terbinafine, naftifine — allylamines

pyributicarb (herbicide) — thiocarbamates — Group 18

H: Cell Wall Biosynthesis

H4: chitin synthase
19 Polyoxins

Peptidyl Pyrimidine nucleoside: Polyoxin — Group 19

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

cinnamic acid amides: dimethomorph, Paraat, flumorph, pyrimorph

valinamide carbamates: iprovalicarb, benthiavalicarb, valifenalate

mandelic acid amides: mandipropamid, Revus — Group 40

P: Host Plant Defence Induction

P01: salicylate related
#P01 benzothiadiazole BTH

acibenzolar-S-methyl — Group P01

P02: salicylate related
#P02 benzothiazole

probenazole — Group P02

P03: salicylate related
#P03 thiadiazole carboxamide

isotianil, tiadinil — Group P03

P04: polysaccharide elicitors
#P04 natural compound

laminarin — Group P04

P05: anthraquinone elicitors
#P05 plant extract

Reynoutria sachalinensis (Giant Knotweed Extract) — Group P05

P06: microbial elicitors
#P06 microbial

Bacillus mycoides (Isolate J): Bacterial *Bacillus* spp.

Cell walls of *Saccharomyces cerevisiae* Strain LAS117 Romeo: Fungal *Saccharomyces* spp. — Group P06

P07: phosphonates
#P07 phosphonates

ethyl-phosphonates: fosetyl-al

Phosphorous acid: H_3PO_3, phosphorous acid — Group P07

P08: salicylate related
#P08 isothiazole

dichlobentiazox — Group P08

M: Chemicals with Multi-Site Activity

Cu — copper preparations — Group M01 — inorganic (electrophiles)

S — Microthiol — Sulphur — Group M02 — inorganic (electrophiles)

chlorothalonil — Group M05 — chloronitriles (unspecified mechanism)

anilazine — Group M08 — triazines (unspecified mechanism)

dithianon — Group M09 — anthraquinones (electrophiles)

dithiocarbamates & relatives (electrophiles): amobam, mancozeb, febram, propineb, metiram, zineb, thiram, methasulfocarb, zinc thiazole, maneb, ziram — Group M03

Group M12 — thiocarbamates (electrophiles)

phthalimides (electrophiles): captan, Captan 80, captafol, folpet — Group M04

dichlofluanid, tolylfluanid — Group M06 — sulphamides (electrophiles)

chinomethionat — Group M10 — quinoxalines (electrophiles)

fluoroimide — Group M11 — maleimides (electrophiles)

guazatine, iminoctadine — Group M07 — bis-guanidines (membrane disruptors, detergents)

mixture of iminoctadine and other polyamines

Unknown Mode of Action

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

cyanoacetamide-oxime: cymoxanil — Group 27

phthalamic acid: teclofталam — Group 34

benzotriazines: triazoxide — Group 35

benzene-sulfonamides: flusulfamide — Group 36

pyridazinones: diclomezine — Group 37

phenyl acetamides: tukumi, cyflufenamid — Group 06

cyano-methylene thiazolidine: flutianil — Group U13

pyrimidinone-hydrazones: ferimzone — Group U14

4-quinolyl acetate: tebufloquin — Group U16

tetrazolyloxime: picarbutrazox — Group U17

glucopyranosyl antibiotic: validamycin — Group U18

guanidines: dodine — Group U12

BM: Biologicals with Multiple Modes of Action

BM 01 : plant extract: Polypeptide (lectin); Phenols, Sesquiterpenes, Triterpenoids, Coumarins; Terpene Hydrocarbons, Terpene alcohols and Terpene phenols — Group BM01

BM 02 : microbial (strains of living microbes or extract, metabolites): Fungal *Trichoderma* spp. T34; Fungal *Clonostachys* spp.; Fungal *Coniothyrium* spp. Contans; Fungal *Hansenia spora* spp.; Fungal *Saccharomyces* spp.; Fungal *Talaromyces* spp.; Bacterial *Erwinia* spp. (peptide); Bacterial *Bacillus* spp. Amylo X, Serenade, Taegro; Bacterial *Gluconobacter* spp.; Bacterial *Pseudomonas* spp.; Bacterial *Streptomyces* spp. — Group BM02

BM 03 : purified metabolites from plant or microbial sources or synthetic versions of these metabolites: cinnamaldehyde — Group BM03

Common names are described in FRAC code list

NC : Not Specified

Mineral oils, organic oils, inorganic salts, material of biological origin — Group NC

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

The groupings can change when new results become known. Colour coded boxes with same group code 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

C8: inhibition of complex III — Target Site and Code

cytochrome bc1(ubiquinone reductase) at Qo site stigmatellin binding sub site) — FRAC Group Name

45 QoSI-fungicide (stigmatellin binding) — Compound (ISO Common Name)

ametoctradin — FRAC Group (#)

triazolo-pyrimidylamine — Chemical or biological group

Group 45

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