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, metalaxyl-M — acylalanines

ofurace — butyrolactones

oxadixyl — oxazolidinones

Group 4

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

bupirimate, 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, carbendazim, thiabendazole

thiophanate, thiophanate-methyl — 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 — pyrimidinamine

tolfenpyrad — pyrazole-5-carboxamide

fenazaquin, quinazoline

Group 39

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

cyano-imidazole: cyazofamid

sulfamoyl-triazole: amisulbrom

picolinamide: fenpicoxamid, florylpicoxamid

Group 21

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

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

fluxapyroxad, furametpyr, penflufen, phenyl-oxo-ethyl thiophene amide

pyrazole - 4 - carboxamides: bixafen, penthiopyrad, isopyrazam, sedaxane, fluindapyr, inpyrfluxam

thiazole - carboxamides: isotetamid, thifluzamide

pyridinyl – ethyl - benzamides: fluopyram, benzovindiflupyr

pyridine - carboxamides: boscalid

oxycarboxin, oxathiin - carboxamides: carboxin

pyrazine - carboxamides: pyraziflumid, isoflucypram, N-cyclopropyl-N-Benzyl-pyrazole-carboxamides

cyclobutrifluram, phenyl-cyclobutyl pyridineamide

benodanil, mepronil, flutolanil

phenyl-benzamides: fenfuram — furan-carboxamides

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

Group 7

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

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

methoxy-acrylates: enoxastrobin, coumoxystrobin, picoxystrobin, pyraoxystrobin, flufenoxystrobin, azoxystrobin

methoxy-carbamates: pyrametostrobin, pyraclostrobin, triclopyricarb

oximino-acetates: kresoxim-methyl, trifloxystrobin

dihydro-dioxazines: fluoxastrobin

oximino-acetamides: orysastrobin, fenaminstrobin, dimoxystrobin, metominostrobin

oxazolidine-diones: famoxadone

dihydro-dioxazines: mandestrobin

imidazolinones: fenamidone

benzyl-carbamates: pyribencarb

methoxy-acetamides

11A QoI fungicides (Quinone outside Inhibitors); Subgroup A: metyltetraprole

Group 11 — Group 11A

D: Amino Acid and Protein Synthesis

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

pyrimethanil, cyprodinil, mepanipyrim

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

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, tebuconazole, hexaconazole, imibenconazole, bitertanol, metconazole, simeconazole, fluquinconazole, tetraconazole, mefentrifluconazole, bromuconazole, myclobutanil, flusilazole, triadimefon, cyproconazole, penconazole, triadimenol, flutriafol, propiconazole, difenoconazole, triticonazole

piperazines: triforine

pyridines: pyrifenox, pyrisoxazole

pyrimidines: nuarimol, fenarimol

imidazoles: imazalil, pefurazoate, trifumizole, oxpoconazole, prochloraz

triazolinthione: prothioconazole

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Group 3

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

piperidines: fenpropidin, piperalin

morpholines: aldimorph, fenpropimorph, tridemorph (n = 10 to 13, n + 12 –70%), 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, flumorph, pyrimorph

valinamide carbamates: iprovalicarb, benthiavalicarb, valifenalate

mandelic acid amides: mandipropamid

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 — Fungal *Saccharomyces* spp.

Group P06

P07: phosphonates
#P07 phosphonates

ethyl-phosphonates: fosetyl-al

Phosphorous acid: phosphorous acid

Group P07

P08: salicylate related
#P08 isothiazole

dichlobentiazox

Group P08

M: Chemicals with Multi-Site Activity

Group M01: copper preparations — inorganic (electrophiles)

Group M02: Sulphur — inorganic (electrophiles)

Group M05: chlorothalonil — chloronitriles (unspecified mechanism)

Group M08: anilazine — triazines (unspecified mechanism)

Group M09: dithianon — anthraquinones (electrophiles)

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

Group M12: thiocarbamates (electrophiles): methasulfocarb

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

Group M06: sulphamides (electrophiles): dichlofluanid, tolylfluanid

Group M10: quinoxalines (electrophiles): chinomethionat

Group M11: maleimides (electrophiles): fluoroimide

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

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: teclofatalam — Group 34

benzotriazines: triazoxide — Group 35

benzene-sulfonamides: flusulfamide — Group 36

pyridazinones: diclomezine — Group 37

phenyl acetamides: 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.; Fungal *Clonostachys* spp.; Fungal *Coniothyrium* spp.; Fungal *Hansenia*spora spp.; Fungal *Saccharomyces* spp.; Fungal *Talaromyces* spp.; Bacterial *Bacillus* spp.; Bacterial *Erwinia* spp. (peptide); Bacterial *Pseudomonas* spp.; Bacterial *Gluconobacter* 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)

ametoctradin — Compound (ISO Common Name)

triazolo-pyrimidylamine — FRAC Group (#)

Group 45 — Chemical or biological group

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