FRAC Classification of Fungicides

FRAC FUNGICIDE RESISTANCE ACTION COMMITTEE

Fungal control agents by cross resistance pattern and mode of action 2022 (www.frac.info)

A: Nucleic Acids Metabolism

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

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: DHODH-fungicides

ipflufenoquin

Group 52

B: Cytoskeleton and Motor Proteins

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

benzimidazoles: benomyl, fuberidazole, carbendazim, thiabendazole

thiophanates: thiophanate, thiophanate-methyl

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 Qo site stigmatellin binding sub site)
45 QoSI-fungicide (stigmatellin binding)

ametoctradin — triazolo-pyrimidylamine

Group 45

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

fluxapyroxad, furametpyr, penflufen — pyrazole -4-carboxamides

phenyl-oxo-ethyl thiophene amide: isofetamid

thiazole-carboxamides: thifluzamide

pyridine-carboxamides: boscalid

pyrazole -4-carboxamides: bixafen, penthiopyrad, fluopyram

pyridinyl-ethyl-benzamides: oxycarboxin, oxathiin-carboxamides, carboxin

benzovindiflupyr, isopyrazam, sedaxane, fluindapyr, inpyrfluxam

pyrazine – carboxamides: isoflucypram, pyraziflumid

N-cyclopropyl-N-Benzyl-pyrazole-carboxamides: fenfuram — furan-carboxamides; pydiflumetofen — N-methoxy-(phenyl-ethyl)-pyrazole-carboxamides

cyclobutrifluram, phenyl-cyclobutyl pyridineamide, benodanil, phenyl-benzamides, mepronil, flutolanil

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)

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

Group 11

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

metyltetraprole

Group 11A

D: Amino Acid and Protein Synthesis

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

cyprodinil, mepanipyrim, pyrimethanil

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

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: tecnazene (TCNB), dicloran, 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)

trifluoroethyl-carbamate: tolprocarb

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, ipconazole, fenbuconazole, tebuconazole, bitertanol, metconazole, fluquinconazole, tetraconazole, bromuconazole, myclobutanil, flusilazole, triadimefon, cyproconazole, penconazole, flutriafol, triadimenol, difenoconazole, propiconazole, hexaconazole, triticonazole, diniconazole, simeconazole, imibenconazole, mefentrifluconazole, epoxiconazole, prothioconazole — triazolinthione

piperazines: triforine

pyridines: pyrifenox, pyrisoxazole

pyrimidines: nuarimol, fenarimol

imidazoles: imazalil, triflumizole, pefurazoate, oxpoconazole, prochloraz

Group 3

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

aldimorph, fenpropimorph, tridemorph (n = 10 to 13, n = 12 – ~70%), dodemorph — morpholines

piperidines: fenpropidin, piperalin

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)

allylamines: terbinafine, naftifine

thiocarbamates: pyributicarb (herbicide)

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: benthiavalicarb, iprovalicarb, valifenalate

mandelic acid amides: mandipropamid

Group 40

Unknown Mode of Action

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

cymoxanil — Group 27 — cyanoacetamide-oxime

tecloftalam — Group 34 — phthalamic acid

triazoxide — Group 35 — benzotriazines

flusulfamide — Group 36 — benzene-sulfonamides

diclomezine — Group 37 — pyridazinones

cyflufenamid — Group 06 — phenyl acetamides

flutianil — Group U13 — cyano-methylene thiazolidine

ferimzone — Group U14 — pyrimidinone-hydrazones

tebufloquin — Group U16 — 4-quinolyl acetate

picarbutrazox — Group U17 — tetrazolyloxime

validamycin — Group U18 — glucopyranosyl antibiotic

dodine — Group U12 — guanidines

P: Host Plant Defence Induction

P1: salicylate related
#P01 benzothiadiazole BTH

acibenzolar-S-methyl

Group P01

P2: salicylate related
#P02 benzothiazole

probenazole

Group P02

P3: salicylate related
#P03 thiadiazole carboxamide

isotianil, tiadinil

Group P03

P4: polysaccharide elicitors
#P04 polysaccharide

laminarin

Group P04

P5: anthraquinone elicitors
#P05 plant extract

Reynoutria sachalinensis (Giant Knotweed Extract)

Group P05

P6: microbial elicitors
#P06

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

Cell walls of *Saccharomyces cerevisiae* Strain LAS117 — Fungal *Saccharomyces* spp.

Group P06

P7: phosphonates
#P07 phosphonates

fosetyl-al — ethyl-phosphonates

H_3PO_3 phosphorous acid — Phosphorous acid

Group P07

P8: salicylate related
#P08 isothiazole

dichlobentiazox

Group P08

M: Chemicals with Multi-Site Activity

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

S — Sulphur — Group M02 — inorganic (electrophiles)

chlorothalonil — Group M05 — chloronitriles (unspecified mechanism)

anilazine — Group M08 — triazines (unspecified mechanism)

dithianon — Group M09 — anthraquinones (electrophiles)

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

methasulfocarb — Group M12 — thiocarbamates (electrophiles)

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

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

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.; Bacterial *Bacillus* spp.; Bacterial *Erwinia* spp. (peptide); Fungal *Coniothyrium* spp.; Fungal *Hanseniaspora* spp.; Bacterial *Pseudomonas* spp.; Bacterial *Gluconobacter* spp.; Fungal *Saccharomyces* spp.; Fungal *Talaromyces* spp.; Bacterial *Streptomyces* spp.

Group BM02

Common names are described in FRAC code list

NC : Not Specified

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

Group NC

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

Legend:

C: Respiration

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

thiazole carboxamides

- 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

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