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Understanding Insecticide Modes of Action and Resistance Management in Florida Horticulture[1]

Hugh Smith, Adam Dale, and Julien Beuzelin [2]

This publication is designed to help UF/IFAS Extension agents and members of the public understand insecticide modes of action and resistance management as they pertain to vegetables, field crops, turf, and ornamental plants.

Mode of Action

The mode of action of an insecticide is the way the insecticide kills an insect. Other definitions include the "means by which a toxin affects the anatomy, physiology, or biochemistry of an organism (Pedigo 2002)," and "the action of an insecticide at its target site (PCT 2021)." Table 1 lists important mode of action groups for insecticides associated with Florida horticulture. It includes examples of trade names by which these insecticides are commonly known in vegetable, row crop, turfgrass, and ornamental plant production and management. Table 1 also indicates pest groups commonly targeted by different mode of action groups. The Insecticide Resistance Action Committee (IRAC) (https://irac-online.org) is an international association thatdefines modes of action and assigns them a number and letter to facilitate resistance management. For example, the neonicotinoids (4A), sulfoximines (4C), and butenolides (4D) are all in group 4, so they all have the same mode of action. Structural differences in the chemical compounds result in these insecticides interacting differently with the target site and being placed into subgroups (A, C, and D).

The mode of action of an insecticide is determined by its active ingredient, which is the chemical compound responsible for the toxic effect. Some mode of action groups such as the pyrethroids (3A) include dozens of active ingredients, while others such as the butenolides (4D) presently contain only one active ingredient (flupyradifurone). Often active ingredients in the same mode of action group are effective against a similar group of target pests. For example, the neonicotinoid (4A) insecticides acetamiprid, imidacloprid, and thiamethoxam are primarily used against piercing-sucking insects such as whiteflies, aphids, and mealybugs. However different active ingredients within the same mode of action group may have distinct targets. Abamectin is a group 6 insecticide that is primarily used against mites and leafminers, while emamectin benzoate, also in group 6, is primarily effective against caterpillars and beetles.

Insecticide Resistance

Repeated exposure to the same mode of action can result in the development of insect and mite populations that are resistant to that mode of action. IRAC defines resistance as "a heritable change in the sensitivity of a pest population that is reflected in the repeated failure to achieve the expected level of control when used according to the label recommendation for that pest species." The risk of insecticide resistance increases when successive generations of a pest are exposed to the same mode of action. Some

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2. Hugh Smith, associate professor, Entomology and Nematology Department, UF IFAS Gulf Coast Research and Education Center; Adam Dale, associate professor, Entomology and Nematology Department; and Julien Beuzelin, assistant professor; Entomology and Nematology Department, UF/IFAS Everglades Research and Education Center; UF/IFAS Extension, Gainesville, Florida 32611.

individuals within any given pest population may be resistant to an insecticide because of genetic ("heritable") factors. Each successive application of that insecticide reduces the susceptible portion of the pest population, so the insecticide-resistant portion gradually predominates if the same mode of action is repeatedly applied. Therefore, it is essential that pesticide applicators be familiar with the mode of action of any insecticide or miticide they apply to offset the development of resistance.

Treatment Intervals

The treatment interval approach to managing insecticide resistance involves grouping modes of action according to the target pest's generation time or life span. The treatment interval is based on an estimate of the pest's life span. The treatment interval approach is used to avoid treating subsequent generations of a pest population with the same mode of action. The same mode of action can be applied more than once during a treatment interval, but during the following treatment interval, a different mode of action should be used, or no insecticides should be applied.

For example, some insecticide labels use a thirty-day treatment interval for diamondback moth (*Plutella xylostella*) management, because thirty days is a good estimate of the diamondback moth's life span. Insect and mite species vary in the time required to complete their life cycle, and mites tend to have shorter generation times than most insects.

For the purposes of resistance management, modes of action should be grouped by number (main group), not letter (subgroup). For example, a neonicotinoid and a butenolide insecticide could be used within the same treatment interval, but no group 4 insecticide should be used in the following treatment interval.

There are many sources of information on pest life cycles, including the University of Florida's Featured Creatures series (https://entnemdept.ufl.edu/creatures/). The publication "Managing Resistance to Diamide Insecticides in Florida Tomato" (https://edis.ifas.ufl.edu/publication/IN978) provides a more detailed description of treatment intervals. Remember that soon after a pest has become established on a crop or plant, pest generations will overlap. It is impossible to completely avoid treating successive generations of a pest with the same modes of action. However, the treatment interval approach provides a framework for reducing the likelihood that resistance will develop. Generation times for a given pest are influenced by temperature and host plant, but for the sake of planning, fixed treatment intervals are used for specific pests.

Key insecticide classes for Florida row crops, vegetables, turfgrasses, and ornamental plants

The IRAC Mode of Action group number for each insecticide class is indicated in parentheses. **Bolded phrases** are explained in the glossary.

For a comprehensive list and description of all currently recognized insecticide modes of action, consult https://irac-online.org.

- Carbamate (1A) and organophosphate (1B) insecticides are broad spectrum insecticides, meaning they will kill most insect groups regardless of their **mouthparts** or **metamorphosis**. These insecticides interfere with pathways in the nervous system that are important for animals, including humans, as well as insects, and so can pose a risk to applicators and field workers. Carbamate and organophosphate insecticides mostly work by **contact**, although there are some **translaminar** and **systemic** insecticides in these two groups. Some carbamates, such as methomyl, and organophosphates, including naled, are **restricted-use insecticides**.
- Pyrethroids (3A) are broad spectrum nerve poisons that work by contact. These are among the most widely used insecticides and are synthetic versions of pyrethrins, insecticidal compounds produced by the plant *Chrysanthemum cinerariifolium*. Synthetic insecticides tend to have a longer **residual efficacy** than naturally occurring compounds, which tend to break down quickly when exposed to sunlight and the elements. Pyrethrins are among the insecticides that can be used in **certified organic** crop production. Many pyrethroids are restricted-use insecticides.
- Neonicotinoids (4A), sulfoximines (4C) and butenolides (4D) are all nicotinic acetylcholine agonists, and so share the same mode of action. Group 4 insecticides are all systemic, and primarily target piercing-sucking insects through ingestion exposure. There are concerns about the impacts of neonicotinoid insecticides on **pollinator health**.
- Spinosyns (5) include spinetoram and spinosad and are primarily used to manage thrips, leafminers, and caterpillars. The active ingredient in Entrust is spinosad, and this formulation is labeled for use in certified organic production. Spinosyns are translaminar and have a mode of action similar to neonicotinoids.
- Avermectins (6) are used against several distinct pest groups. Abamectin, an insecticide-miticide, is one of the most widely used materials to manage spider mites

(*Tetranychusurticae* and other species) and *Liriomyza* leafminers.

- Pyriproxyfen (7C) is a juvenile hormone mimic that interferes with the processes by which insects hatch from the egg and develop from one larval or nymphal stage to the next. Juvenile hormone mimics are **insect growth regulators** and do not affect adult insects other than to reduce the viability of eggs produced by exposed females. Pyriproxifen is used primarily against whiteflies, scale insects, and ants, with some activity against caterpillars. Pyriproxifen has translaminar activity.
- Chordotonal modulators (9) interfere with the functioning of stretch receptors in insects that influence movement and feeding. They are translaminar and are primarily used against aphids and whiteflies.
- Mite growth inhibitors (10) interfere with the ability of mites to form chitin, a key ingredient in the exoskeleton of arthropods (Nauen and Smagghe 2006). Mite growth regulators are effective against egg and protonymph spider mites. They function by contact.
- *Bacillus thuringiensis* (11A) products consist of the *B. thuringiensis* (Bt) bacterium and crystal proteins, called delta endotoxins, produced by the naturally occurring bacterium. These proteins bind to receptor sites in the stomach when ingested by a target insect, causing the stomach wall to rupture. In agriculture, Bt products are used primarily against caterpillars. The two most used subspecies of Bt are *aizawi* and *kurstaki*. The Bt subspecies *israelensis* is used against fungus gnats (*Bradysia* spp.). Most formulations of Bt are registered for use in certified organic crop production, but some (for example Crymax) are not. Bt products are very specific to the pests they target because other organisms lack the binding sites in the stomach area that are affected by the crystal protein.
- Benzoylureas (15) are insect growth regulators that interfere with the insect's ability to form chitin. They are used against a limited number of insect groups, including caterpillars, beetle larvae, grasshoppers, and psyllids. Adult stages are not affected. Group 15 insecticides function differently from insect growth regulators in other mode of action groups. They function by contact.
- Buprofezin (16) is an insect growth regulator that interferes with the insect's ability to form chitin. It is used to manage leafhoppers, planthoppers, whiteflies, scale insects, and mealybugs. Only the immature (nymphal) stages of the pest are affected. Group 16 insecticides function differently from insect growth regulators in other mode of action groups. Buprofezin functions primarily by contact.
- Cyromazine (17) disrupts molting, the progression from one life stage to the next, in dipteran (fly) leafminer (*Liriomyza* spp.) larvae. It is also labeled for management of Colorado potato beetle (*Leptinotarsa decemlineata*) larvae in some crops. It is a contact insecticide.
- Diacylhydrazines (18) interfere with the functioning of ecdysone, an insect prohormone involved in molting and metamorphosis. These insecticides are used to manage caterpillars and function by contact.
- METI insecticides (20, 21) interfere with electron transport in the mitochondria. Important insecticides in this group include bifenazate, which is used to manage spider mites, as well as fenpyroximate and tolfenpyrad, which are used against several distinct pest groups. They are contact insecticides.
- Indoxacarb (22A) is a sodium channel blocker, interfering with sodium metabolism. It is primarily used against caterpillars and mole crickets. It is a contact insecticide.
- Lipid biosynthesis inhibitors (23) include spiromesifen and spirotetramat, which are used against mites, whiteflies and other pests. These materials have systemic activity.
- Cyflumetofen (25) interferes with electron transport in the mitochondria. It is registered for use in a limited number of crops for management of spider mites and other mite groups. It is translaminar.
- Diamides (28) interfere with the functioning of ryanodine receptors, which are important in the regulation of calcium. Most diamides are systemic. They vary with regard to the spectrum of pests they affect. Some diamides are commonly used for management of caterpillars and beetles (e.g., chlorantraniliprole, tetraniliprole), and others are used for management of piercing-sucking insects (e.g., cyantraniliprole).
- Flonicamid (29) is a chordotonal modulator but functions differently from the group 9 insecticides. It has some systemic activity.

Insecticides and IPM

Insecticides are only one component of an integrated pest management program. Crops and plants are ideally monitored weekly to determine if pests are present and increasing to damaging numbers. Crops vary in their tolerance to pests. Farm and nursery managers vary in their tendencies to tolerate pest damage. Pests that do not transmit viruses can generally be tolerated at higher levels than insect vectors of disease.

For most of Florida's high-value specialty crops, insecticides play a leading role in reducing damage and losses due to insects and mites. Conditions for pests are favorable almost year-round in Florida, and for this reason sanitation and clean culture play an important role in reducing habitat for pests. Harvested fields and plants in a nursery or greenhouse that are no longer marketable should be promptly destroyed so that they do not serve as a source of pests or disease. Commercial varieties of some crops have **host plant resistance** to viruses and other pathogens transmitted by arthropods.

Many pests in Florida are attacked by naturally occurring **predators** and **parasitoids**, and these **natural enemies** can help reduce pest populations. Some commercially available **biological control agents** can be purchased and released to help manage pests in some crop systems. Insecticidal soaps and oils can also be incorporated into insecticide rotations to help manage some pests. These **biopesticides** reduce arthropod numbers in ways that pests generally do not develop resistance to, and therefore are not assigned a mode of action number as conventional insecticides are. Most biopesticides are acceptable for use in certified organic crop production and have limited negative impacts on natural enemies and pollinators compared to conventional insecticides when used according to the label.

Insecticide use planning starts with the label. *The label is the law*. Many labels have pollinator protection instructions that restrict how and when the insecticide can be applied. Decisions regarding insecticide use are determined by many factors, including the seasonal stage of the crop or plant, risks to pollinators, days to harvest, and which insecticides have already been applied. The ability to manage arthropod pests primarily with insecticides is also influenced by the duration of the crop or plant. The likelihood that insecticide resistance will develop on perennial crops or landscape plants that are treated for years is higher than the risk of resistance developing on an annual vegetable crop that is only in the ground for a few months. However, vegetable crops in Florida are usually grown in multiple staggered plantings so that pest populations on a given farm or adjacent group of farms are exposed to insecticides for multiple generations over several months of the production season. This can also result in resistant pest populations over time. Familiarity with local conditions, grower practices and the seasonality of pest populations is useful for planning insecticide programs and offsetting the development of insecticide resistance.

Glossary

Biological control agents are predators, parasitoids, nematodes, and pathogens that attack arthropod pests and can be mass reared and sold by commercial production facilities. Biocontrol agents are released or applied to production areas, often repeatedly, for management of arthropod pests.

Biopesticides include insecticidal soaps, oils, and botanical insecticides such as azadirachtin and neem products. Biopesticides also include microbial pathogens such as *Bacillus thuringiensis* (Bt) and the insect fungal pathogens *Beauveria bassiana* and *Paecilomyces fumosoroseus* that have been formulated to be applied as insecticides.Most biopesticides kill in a way that does not select for resistance and so are not assigned an IRAC mode of action number. The notable exceptionsare the Bt products, which have the mode of action number 11A. Biopesticides tend to have a shorter residual efficacy than conventional insecticides, and most are labeled for use in certified organic production.

Certified organic production complies with United States Department of Agriculture regulations for organic production (https://www.ams.usda.gov/services/organic-certification/certification). Organic farming avoids synthetic inputs and emphasizes naturally evolved soil and crop processes (https://www.ams.usda.gov/grades-standards/organic-standards).

Contact insecticides kill an insect when the insect comes in direct contact with the insecticide or its active residues.

Host plant resistance involves breeding heritable characteristics into crop plants, enabling them to produce marketable yields when exposed to levels of pest or disease that would cause economic losses in susceptible varieties.

Insect growth regulators are insecticides that interfere with the hormonal and enzymatic processes that direct the development of arthropods from one life stage to the next.

Metamorphosis is the process of changing in form through life stages to become an adult. Some insects like grasshoppers and stinkbugs pass through a simple or incomplete metamorphosis in which the immature stages (nymphs) look similar to the adult but lack wings. Insects like moths and beetles have complete metamorphosis and pass through four completely distinct life stages: egg, larva, pupa, and adult. The type of metamorphosis an insect pest passes through has a direct bearing on methods to monitor, identify, and manage the pest.

Mouthparts vary among different arthropod groups. Beetles, caterpillars, and grasshoppers are among the insects with chewing mouthparts. Aphids, whiteflies, and mites have piercing-sucking mouthparts. Thrips have rasping-sucking mouthparts. The type of mouthpart an insect has influences the damage it causes and the likelihood that it will ingest a specific type of insecticide.

Natural enemies of an insect or mite are the naturally occurring predators, parasitoids, nematodes, and pathogens (diseases) that attack and kill it in nature. Pesticide selection and application practices can be modified to limit impacts on natural enemies.

Parasitoids are insects that lay eggs inside or on other host insects. The parasitoid egg hatches and the parasitoid larva completes its development inside the insect host, initially feeding on host fluids but eventually feeding on the host's tissue and killing it. The parasitoid larva then emerges from the host insect to complete its development, often forming a pupa within or on the host carcass. Most parasitoids are wasps or flies. Wasps use their ovipositor to insert the egg inside the host. Flies lack an ovipositor, and so lay their eggs on the body of the host. Parasitic fly larvae must burrow into the host to complete their development after hatching from the egg.

Pollinator health refers to the survival, reproduction, and abundance of pollinators. Pollinator health has become a global concern in recent decades due to the decline in populations of western honeybees (*Apis mellifera*) and many native bee species. Insecticides are one of several factors associated with these population declines.

Predators are insects and mites that attack and feed upon other arthropods, consuming multiple prey during their life cycle.

Residual efficacy refers to the period in days or weeks after application that an insecticide continues to reduce populations of a given pest.

Restricted-use insecticides can only be used by a certified pesticide applicator or under the supervision of a certified applicator. Insecticides are grouped in this category because of risks associated with human and environmental health.

Systemic insecticides enter treated plants through the roots or foliage and are distributed within the plant via the vascular system. Systemic insecticides tend to have a longer residual efficacy than contact or translaminar insecticides.

Translaminar insecticides can move from the side of the plant leaf where they are applied to the other side of the leaf and are also referred to as "locally systemic." Translaminar insecticides tend to have a longer residual efficacy than contact insecticides.

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Table 1. Important insecticide classes and their mode of action with example active ingredients, trade names, and target pests.

IRAC MoA Code	Chemical Class† Mode of action	Example active ingredients	Horticultural trade name examples	Turf/ornamental trade name examples	Target Pests
1A	Carbamates Acetylcholinesterase inhibitor	carbaryl	Sevin 4F	Sevin SL	Broad spectrum
		methomyl	Lannate SP		
1B	Organophosphates Acetylcholinesterase inhibitor	acephate	Orthene	Orthene, Precise	Broad spectrum
		chlorpyriphos	Lorsban	Dursban 50W	
		naled	Dibrom	N/A	
		diazinon	Diazinon AG500	N/A	
		malathion	Malathion 5EC	Malathion 5EC	
		dimethoate	Dimethoate 4EC		
		trichlorfon		Dylox	
3A	Pyrethroids Sodium channel modulator	bifenthrin	Brigade 2 EC, many generics	Talstar S, Bifen XTS, many more	Broad spectrum
		cyfluthrin		Decathlon, Tempo	
		beta-cyfluthrin	Baythroid XL	Tempo Ultra	
		esfenvalerate	Asana XL		
		lambda-cyhalothrin	Warrior II	Demon WP, Demand CS	
		cypermethrin		Demon	
		zeta-cypermethrin	Mustang Maxx	Sevin, Triple Crown T&O (plus bifenthrin, imidacloprid)	
		deltamethrin		DeltaGard	
		tau-fluvalinate		Mavrik	
		permethrin		Astro, Permethrin	
3A	Pyrethrins Sodium channel modulator	pyrethrin	Pyganic	Pyganic, Tersus	Broad spectrum
4A	Neonicotinoids Nicotinic acetylcholine receptor competitive modulator	acetamiprid	Assail	TriStar	Piercing sucking insects, some beetles, and some thrips
		clothianidin	Belay	Arena, Aloft (plus bifenthrin)	
		dinotefuran	Venom	Safari, Zylam, Transtect	
		imidacloprid	Admire Pro, many generics	Merit, Marathon, others	
		thiamethoxam	Actara, Platinum	Meridian, Flagship	
4C	Sulfoxamines Same as neonicotinoids	sulfoxaflor	Closer, Transform	XXpire (+spinetoram)	Piercing sucking insects
4D	Butenolides Same as neonicotinoids	flupyradifurone	Sivanto Prime, Altus	Altus	Piercing sucking insects and some thrips
5	Spinosyns Nicotinic acetylcholine receptor allosteric modulator – Site I	spinetoram	Radiant SC	XXpire (+sulfoxaflor)	Thrips, caterpillars, and leafminers
		spinosad	Entrust, Blackhawk	Conserve, Entrust	
6	Avermectins Glutamate-gated chloride channel allosteric modulator	abamectin	Agri-Mek, generics	Avid Lucid Divanem Award II, Sirocco	Varies according to active ingredient: check label.
		emamectin benzoate	Proclaim	Tree-age Arbormectin Enfold	

IRAC MoA Code	Chemical Class† Mode of action	Example active ingredients	Horticultural trade name examples	Turf/ornamental trade name examples	Target Pests
7C	Pyriproxyfen Juvenile hormone mimic	pyriproxyfen	Knack	Esteem Distance Fulcrum Nygard	Juvenile stages of various pests including whiteflies, caterpillars, and ants. Check label.
9B	Pyridine azomethine derivatives Chordotonal organ TRPV channel modulator	pymetrozine	Fulfill	Endeavor	Primarily aphids and whiteflies
		pyrifluquinazon	PQZ	Rycar	
9D	Pyropenes Chordotonal organ TRPV channel modulator	afidopyropen	Sefina, Versys	Ventigra	
10A	†Hexythiazox Mite growth inhibitors affecting CHS1	hexythiazox	Savey 50 DF	Hexygon DF	Spider mites
10B	†Etoxazole Mite growth inhibitors affecting CHS1	etoxazole	Zeal	Beethoven TR TetraSan	
11A	*Bacillus thuringiensis* and the insecticidal proteins they produce Microbial disruptor of insect midgut membrane	*Bacillus thuringiensis* aizawi strain	XenTari, Agree WG	XenTari	Caterpillars
		B. thuringiensis galleriae		grubGONE! G	Beetles
		B. thuringiensis israelensis		Gnatrol	Flies
		B. thuringiensis kurstaki strain	Dipel DF, Javelin WG	Dipel Pro DF	Caterpillars
15	Benzoylureas Inhibitors of chitin biosynthesis affecting CHS1	Novaluron	Rimon	Pedestal, Suprado	Caterpillars and juvenile stages of some beetles, thrips, whiteflies, and other sucking insects
		Diflubenzuron	Dimilin 2L	Dimilin 4L	
16	†Buprofezin Inhibitors of chitin biosynthesis, Type 1	buprofezin	Courier	Talus 70DF	Juvenile stages of whiteflies, scales, mealybugs, planthoppers, and leafhoppers
17	†Cyromazine Moulting disruptor, dipteran	cyromazine	Trigard	Citation	Fly larvae and Colorado potato beetle larvae
18	Diacylhadrazines Ecdysone receptor agonist	methoxyfenozide	Confirm 2F	Intrepid 2F	Caterpillars
		tebufenozide	Intrepid 2F	Confirm 2F	
20A	Mitochondrial complex III electron transport inhibitors	Hydramethylnon	Amdro ProExtinguish	Amdro ProExtinguish	Fire ants
20B	†Acequinocyl Mitochondrial complex III electron transport inhibitors	acequinocyl	Kanemite 15 SC	Shuttle	Spider mites and broad mites
20D	†Bifenazate Mitochondrial complex III electron transport inhibitors	bifenazate	Acramite 50WS	Floramite Sirocco	Spider mites
21A	METI acaricides and insecticides Mitochondrial complex I electron transport inhibitor	pyridaben	Nexter	Sanmite	Broad mites, rust mites, spider mites, and whiteflies
		fenpyroximate	Portal XLO	Akari	
		Tolfenpyrad	Torac	Hachi-Hachi SC	

IRAC MoA Code	Chemical Class[†] Mode of action	Example active ingredients	Horticultural trade name examples	Turf/ornamental trade name examples	Target Pests
22A	[†]Indoxacarb Voltage-dependent sodium channel blockers	indoxacarb	Avaunt eVo	Advion Provaunt	Caterpillars, fire ants, and mole crickets
23	Tetronic and tetramic acid derivatives Inhibitors of acetyl COA carboxylase	spiromesifen	Oberon	Forbid Judo	Whiteflies, russet mites, spider mites, and others
		spirotetramat	Movento	Kontos	
25	[†]Cyflumetofen Mitochondrial complex II electron transport inhibitors	cyflumetofen	Nealta	Sultan	Spider mites
28	Diamides Ryanodine receptor modulators	chlorantraniliprole	Coragen, Vantacor	Acelepryn	Caterpillars, leafminers, some piercing sucking insects, and turf weevils
		cyantraniliprole	Verimark, Exirel	Mainspring	
		cyclaniliprole	Harvanta		
		Tetraniliprole		Tetrino	
29	[†]Flonicamid Chordotonal organ modulators – undefined target site	flonicamid	Beleaf, Carbine	Aria	Aphids

[†] If the group is represented by only one active ingredient, or if primarily one active ingredient is pertinent for Florida crop production, the active ingredient is listed here as well as in the active ingredient column.