W415

The Insecticide and Miticide Mode of Action Field Guide

A Resource to Assist in Managing Arthropod Pests of Turfgrass and Ornamental Plants

Muhammad "Zee" Ahmed, Assistant Professor, Pee Dee Research and Education Center, Clemson University
Bill Klingeman, Professor, Department of Plant Sciences, The University of Tennessee
Midhula Gireesh, Assistant Professor, Department of Entomology and Plant Pathology, The University of Tennessee
Juang Horng "JC" Chong, Technical Product Manager, SePRO Corporation

(Original version with contributions by Frank Hale, Professor Emeritus, Department of Entomology and Plant Pathology, The University of Tennessee)

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The Insecticide and Miticide Mode of Action Field Guide (W 415) was developed as a companion to publication W 329 ("*An Ornamental Plant Pest Management Guide and Pesticide Rotation Planning Aid: Control Options for Nursery, Greenhouse, Interiorscape and Commercial Landscape Use Sites*," solutions.tennessee.edu/publication/W329). This document describes the mode of action and discusses the function of insecticides and miticides that are available for use against arthropod pests infesting turfgrasses and ornamental plants in nurseries, greenhouses, interiorscapes, landscapes[1,2].

Development of Pesticide Resistance

Pesticide resistance reduces the effectiveness of a particular pesticide (insecticide, fungicide, herbicide, and others) after repeated and typically long-term uses of the pesticide. Pesticide resistance arises from a reduction in the susceptibility of a pest population to a particular pesticide. This reduction in susceptibility is the product of two interacting factors – pesticide **mode of action (MOA)** and pest genetic plasticity.

Most insecticides and miticides (also called acaricides) affect one of the four essential biological processes or systems in arthropods: 1) the nervous system; 2) metabolic energy production; 3) growth; and 4) physiological or structural function (including feeding and water balance). After insecticide molecules enter the arthropod's body, either through the cuticle (contact poisons), through spiracles (fumigation), or by ingestion (stomach poisons), the

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[1] Chemical subgroups presented within this document are based on **Insecticide Resistance Action Committee (IRAC)** classifications (irac-online.org/mode-of-action)

[2] *Disclaimer*: Active ingredients are the focus of this document; any mention of active ingredients or product names of insecticidal and miticidal products does not imply approval, endorsement or guarantee of the products. Use pesticides only according to the directions on the label. Follow all directions, precautions, and restrictions that are listed.

molecules bind to specific enzymes or receptors in cells. Once bound, the insecticide molecules disrupt or alter neural, metabolic, developmental, or other physiological functioning within the pest, eventually leading to the death of the treated pest.

Although insects (or mites) in a population look almost identical to each other, the individuals will differ slightly either by the genes they carry or how those genes may function. This genetic variation confers different abilities to alter physiological function in response, for example, to environmental or other stressors including toxins. Some individuals may carry 'resistance' genes or possess genetic mutations that help them tolerate a given insecticide stressor. These individuals may be better able to modify slightly the concentration or structure of the enzymes or receptors targeted by the insecticide. In turn, these slight modifications can reduce or neutralize the ability of the pesticide molecules to bind to the receptor sites. In essence, these genetic mutations or resistance genes sustain normal and essential physiological functioning, thus enabling the pest to survive the toxic effects of the insecticide. When insecticide-resistant individuals reproduce, they can pass on the 'resistance' genes to the next generation. If the same stress continues to affect the population across several generations, a greater proportion of susceptible individuals will die, yet more resistant individuals will survive and reproduce. In other words, long-term use of the same pesticide functions as a continuous selection factor that enables a population to become increasingly resistant to the pesticide. Operationally, a pest manager may observe reduced efficacy of the pesticide across time.

The risk of developing pesticide resistance is greater in pests that reproduce rapidly, such as aphids, mites, thrips and whiteflies that produce high numbers of offspring across multiple generations within a growing season. The risks of pesticide resistance are greater yet where these pests are contained within a monoculture crop or enclosed production system, like a greenhouse, where interbreeding with wild-type or susceptible individuals is restricted. Under these conditions, there is higher likelihood that a pesticide-resistant individual of one gender will find a pesticide-resistant mate.

Cross-resistance occurs when a single or a series of genetic mutations that confers resistance to one insecticide also provides resistance to another insecticide. Among ornamental plant pests, for example, a small population of western flower thrips (*Frankliniella occidentalis*) with resistance to imidacloprid can also demonstrate cross-resistance to acetamiprid to which it may not have been exposed. Both of these insecticides are neonicotinoid active ingredients classified in Insecticide Resistance Action Committee's Mode of Action group 4A (IRAC 4A). **Multiple resistance** can occur when a pest becomes resistant to more than one pesticide mode of action after prolonged and sequential exposure to multiple chemical classes with different modes of action. In an extreme example, a single diamondback moth strain (*Plutella xylostella* CH1) has developed cross-resistance to spinosyns (IRAC 5), abamectin (IRAC 6), and *Bt* insecticides (IRAC 11).

Regardless, managing other populations of high resistance-risk species, including western flower thrips, may warrant additional efforts at pro-active pesticide rotation planning that feature use of different pesticide modes of action. See Table 1 for a list of high resistance-risk pest species and guidelines on sustainable IRAC class selection.

Table 1. A list of high resistance-risk arthropod species and potential cross-resistant chemical classes.

Example pest species	**Pest management applications made from IRAC Group (a.i.):**	**Are best when *not preceded by/or followed by* products applied from IRAC Group (a.i.)**
Western flower thrips	1B (chlorpyrifos)	3A (cyhalothrin), 6 (abamectin)
Green peach aphid	4A (neonicotinoids)	4C (sulfoxaflor), 4D (flupyradifurone)
Glasshouse & silverleaf whiteflies	4A (neonicotinoids)	9B (pymetrozine)
Panonychus spider mites	10A (clofentazine, hexathiazox) 10B (etoxazole)	15 (diflubenzuron, novaluron)
Twospotted spider mite	20D (bifenazate)	20B (acequinocyl)

Pest resistance to insecticides and acaricides is a real and growing concern. Efforts to limit pesticide resistance should be an active part of pest manager's decision-making process. The "Arthropod Pesticide Resistance Database" is a searchable tool (pesticideresistance.org) that compiles and shares published evidence about species, conditions, and geographic locations where pest resistance to pesticides has been documented. Frequently encountered ornamental plant pest species, including twospotted spider mites, western flower thrips, sweetpotato whiteflies, and green peach aphids, are among the top 12 species that have developed resistance to multiple pesticide active ingredients spanning several chemical classes.

How Can You Avoid or Delay Pesticide Resistance?

A plant producer or pest manager can avoid or delay the development of pesticide resistance by following a few **Best Practice** guidelines:

1. Adopt an integrated pest management (IPM) approach to establishing and managing landscapes:
    a. Strive to apply pesticides only when needed to limit aesthetic or economic losses;
    b. Select pesticides that complement cultural and biological control tactics; and
    c. Where available, use pest resistant and less-susceptible host plants;
2. Apply pesticides at the recommended rates and achieve thorough coverage;
3. Target pests when they are at their most susceptible life stage;
4. Rotate among pesticides that provide different MOA and change to a different MOA for each pest generation;
5. If a tank mix is desired, choose pesticides with different MOA;
6. Use combination products that contain active ingredients of different MOA; and

7. Do not reapply with a pesticide of the same MOA when you perceive that pest susceptibility to that pesticide has become noticeably reduced.

Pesticide resistance can often be at least partially reversed. **Reversal** may occur in two ways. First, stop using the failed pesticide MOA for several generations. Most physiological modifications that confer pesticide resistance can be functionally costly to the resistant pest. These costs add up as a consequence of reduced metabolic efficiency, an increase in energy expenditures for survival, or as a reduction in reproduction or fitness. Once the stressor (i.e., the pesticide) is removed, the lower performing but resistant individuals may be gradually outcompeted by higher performing but less resistant individuals. The second way reversal may occur is through migration of susceptible individuals from another population and the dilution of resistant individuals. This reversal mechanism may occur in an open environment where wild-type, susceptible individuals can enter to reproduce. As the susceptible and resistant individuals mate, the resistant genes are further diluted.

Understanding Mode of Action and the IRAC Classification Scheme

Exploiting physiological **Modes of Action (MOA)** to assist in managing pest organisms provides the conceptual foundation for a pesticide resistance management program. Pesticide resistance often arises from repeated use of a single MOA. A practical solution to avoiding pest resistance is to use pesticides with different MOA to manage each pest generation. In other words, to practice pesticide rotation.

Insecticides and miticides are grouped into various **chemical classes** (sometimes called chemical groups or chemical families) according to their chemical similarities. For example, acephate, chlorpyrifos and trichlorfon are all members of the organophosphate chemical group because these compounds are very similar chemically, molecularly and functionally. Often, several chemical classes share the same MOA because they kill insects and mites through the same biochemical processes or pathways.

To facilitate the design of an appropriate pesticide rotation program, the **Insecticide Resistance Action Committee (IRAC)** classifies all manufactured insecticidal and acaricidal chemicals according to their MOA. Each MOA is categorized with a unique group number and chemical class within a single MOA group may receive a unique number-letter combination (see W 329, (solutions.tennessee.edu/publication/W329). For example, carbamates are classified as 1A, whereas organophosphates are classified as 1B. The same number ("1") indicates that carbamates and organophosphates are of the same MOA (acetycholinesterase inhibitors) but the different letters ("A" vs. "B") indicate that they are of different chemical classes. A pest manager who uses acephate (an organophosphate, 1B) against a pest population should rotate to a product of different MOA or IRAC group number (e.g., dinotefuran, a neonicotinoid, or 4A) against the next generation, not to one of the same MOA (e.g., carbaryl, a carbamate, or 1A). This Field Guide will only address those Chemical Subgroups for which there is an active ingredient that is labeled for Use Sites associated with production or maintenance of ornamental plant species.

Although not required by law, pesticide manufacturers are encouraged to prominently display the IRAC MOA group number on their product labels. Many newer products do include such labeling and our section headings reflect this convention. The inclusion of IRAC MOA group

number is extremely helpful in clearly informing the pest managers and applicators about the MOA of the product and assisting them in selecting appropriate pesticides in accordance to pesticide resistance management guidelines.

How Can Knowing about Mode of Action Improve Your Likelihood of Successful Pest Management?

A better understanding about how insecticides or miticides kill their target pests is important in selecting the most efficacious chemicals to manage the target pest. The best pest managers share a fundamental understanding about pesticide modes of action. This knowledge helps the pest manager to develop a pesticide rotation program that will help prevent or delay the development of pesticide resistance in the target pest populations.

Notes on Pollinator Conservation

Concerns raised about the safety of neonicotinoid insecticides to pollinating insects interacting with treated plants has increased dialogue and research about the status and health of pollinators including honey bees, bumble bees and native bee species in the United States. Pesticide applicators are expected and legally required to read and follow the application restrictions listed on the label. In general, it is prudent practice to take steps that reduce exposure of pollinators to pesticides, and especially insecticides, including:

- not applying neonicotinoids and broad-spectrum insecticides to flowering plants if the plants are attractive to foraging pollinators, or if pollinators are observed on the plants
- minimizing direct exposure to foraging pollinators to applied pesticides
- controlling flowering of broadleaf weeds with herbicides or by mowing prior to application of insecticides to turfgrass
- minimizing pesticide spray drift to beehives and onto pollinator-attractive plants (e.g., through short-term use of opaque tarps to cover flowering plants)

The Horticultural Research Institute has released *Best Management Practices (BMPs) for Bee Health in the Horticultural Industry*, which includes guidelines for protecting pollinators in ornamental plant and turfgrass systems: hriresearch.org/Pollinate-Research-and-Resources

Protecting and Enhancing Pollinators in Urban Landscapes (MSU Extension Bulletin E3314) was developed for the US North Central Region and provides practical information that is broadly applicable in the eastern US.
msue.anr.msu.edu/uploads/236/78920/ProtectPollinatorsInLandscape_FINAL-HigherRes.pdf

Check for updates to the Protecting Bees: Best Management Practices Archive at (protectingbees.njaes.rutgers.edu/resources/best-management-practices/) and the Pollinator Stewardship Project, available at the Horticultural Research Institute (HRI) Initiatives website (www.hriresearch.org/HRI/Research/Special_Initiatives.aspx).

GROUP 1 INSECTICIDE

GROUP MODE OF ACTION

Acetylcholinesterase inhibitors

IRAC CHEMICAL SUBGROUPS[1]

Carbamates (1A); Organophosphates (1B)

General Group Profile

Broad spectrum, contact insecticide; quick knockdown; some active ingredients (e.g., acephate, dicrotophos and oxydemeton methyl) may have moderate systemic activity and translocation within plant tissues.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(1A) carbaryl, *methiocarb**; (1B) acephate, chlorpyrifos, dicrotophos, dimethoate, malathion, *oxydemeton methyl**, trichlorfon

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How the Chemistry Works Within the Pest

Carbamates and organophosphates are nerve poisons that work by disrupting the normal transmission of nerve impulses and signals. When functioning properly, nerve impulses cross the synaptic gap between nerve cells by way of a neurotransmitter called acetylcholine. When an electrical nerve signal arrives at the end of a nerve cell, the nerve cell releases acetylcholine molecules, which travel across the synaptic gap and bind with receptors on the next nerve cell, triggering the generation of electrical nerve signal that then travels the length of the next nerve cell. Once the signal is transmitted, acetylcholinesterase (an enzyme) degrades acetylcholine molecules so that nerve signals are no longer fired. Carbamates and organophosphates inhibit the action of acetylcholinesterase. As a result, the acetylcholine molecules accumulate and continue to stimulate receptors into generating nervous impulses.

How You Might Observe that Treatments are Working

Typical symptoms of continuous nerve stimulation (hyperexcitation) that is apparent in treated insects, which display hyperactivity and rapid twitching of voluntary muscles. Eventually, over-stimulation will lead to respiratory failure, paralysis, and then death.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products. Italicized A.I.s followed by an asterisk may no longer be available commercially.

General Notes on Target Arthropods

Wide pest range that includes caterpillars, beetles, sawflies, leafminers, and some mites,with good efficacy against sucking insects (like scale insects, aphids, and lace bugs).

Notes on Interactions with Non-Target Arthropods

Carbamates and organophosphates have high acute toxicity (thus a quick knockdown of both pests and non-target arthropods, and are also highly toxic to mammals). Products have varying durations of persistence in the environment. For example, malathion has a half-life (i.e., the amount of time needed to break down 50 percent of the compound in the environment) of 2-17 days in water and 1-17 days in the soil, whereas the half-life of diazinon is 12 hours (in high acidity) to 6 months (in neutral pH) in water and 2-4 weeks in the soil. The long persistence of carbamate and organophosphate pesticides in the soil and water means that a concentration lethal to the non-target organisms may be present within the period of persistence, thus posing significant risks to non-target organisms in those environments.

Origin and History

Carbaryl was the first carbamate introduced in 1956. Organophosphate insecticides were derived from products of nerve gas research during World War II. Malathion, which was introduced in 1950, is among the oldest organophosphates still in use. Products containing methiocarb have been withdrawn from registered use in nursery and landscape sites as of 2023.

Current Status

Being some of the oldest pesticides, there are a large number of carbamates and organophosphates still in use in the green industry. Carbaryl, acephate, malathion and trichlorfon are still some of the most commonly used pesticides. Non-agricultural uses of others in landscapes either require specialized equipment or injection technologies (dicrotophos and methidathion), or have been greatly restricted (e.g., chlorpyrifos, dimethoate, and methiocarb) or cancelled (*e.g.*, diazinon and oxydemeton methyl) by U.S. EPA in recent years following concerns related to acute mammalian toxicity and environmental risks from these compounds. The trend in phasing-out the carbamates and organophosphates will likely continue.

GROUP 2 INSECTICIDE

GROUP MODE OF ACTION

Gamma-aminobutyric acid (GABA)-gated chlorine channel blockers

IRAC CHEMICAL SUBGROUPS[1]

Cyclodiene organochlorines (2A);
Phenylpyrazoles and Fiproles (2B)

General Group Profile

Chemicals in this group are primarily stomach poisons (only limited dermal exposure) and act very slowly. The slow action of fipronil allows this chemical to be formulated as baits for many structural pests; the slow action allows the foraging individuals to survive for some time and carry the baits back to the colony. Fipronil also appear to have repellency against some common turfgrass insect pests.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(2A) *endosulfan**; (2B) fipronil

How the Chemistry Works Within the Pest

When functioning normally, gamma-aminobutyric acid (GABA) binds to post-synaptic receptor proteins at the end of nerve cells and enables chlorine channels to open, allowing chlorine ions to flow into the nerve cell and dampen nerve impulses. On application, Group 2 insecticides bind to GABA receptors, leading to continuous closure of chlorine channels. Synaptic responses are inhibited, eventually causing the nervous system to become paralyzed.

How You Might Observe that Treatments are Working

Insects become hyper-excited, twitch convulsively, and eventually die.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products. Italicized A.I.s followed by an asterisk may no longer be available commercially.

General Notes on Target Arthropods

In the green industry, fipronil is used as an effective, long-lasting management tool against red imported fire ant, nuisance ants, mole crickets, fleas and ticks.

Interactions with Non-Target Arthropods

Fipronil also has high environmental risks and must be used carefully. Fipronil is highly toxic to fish, aquatic invertebrates, bees and other pollinators.

Additional Notes for Optimal Deployment

For best results, fipronil granules should be wetted and dissolved (by rainfall or irrigation) shortly after application to facilitate formation of a protective layer on the soil surface. Subsequent soil disruption (e.g., tillage or aerification) in treated areas should be minimized to avoid disrupting the protective layer.

Origin and History

Fipronil was discovered in 1987 and commercialized in 1993. This is now the only insecticide in this group that is still been used in the green industry, primarily on the turfgrass and occasionally on fire ant quarantine treatment in nurseries. Fipronil is also used extensively in structural (e.g., against termites) and veterinary pest management (e.g., monthly flea and tick treatment for pets). Endosulfan is a cyclodiene organochlorine (2A) developed in 1956. In the past, endosulfan was used extensively in the turf and ornamental industry for aphid, whitefly, borer and mite management. Endosulfan is now banned in the U.S. because of its acute neurotoxicity to human and other mammals. In some references, DDT was considered a member of the organochlorine chemical class (2A). However, the most current IRAC grouping places DDT as a chemical class within Group 3B.

Current Status

Fipronil is a phenylpyrazole (2B) that is the only commercially available product in this group labeled for commercial nursery or professional landscape management. EPA has put stringent restrictions on use site and requirement for buffer zone to minimize negative impacts of fipronil on aquatic invertebrates.

GROUP 3 INSECTICIDE

GROUP MODE OF ACTION

Sodium channel modulators

IRAC CHEMICAL SUBGROUPS[1]

Pyrethrins, Pyrethroids (3A)

General Group Profile

Pyrethroids have a broad spectrum of contact toxicity and quick knockdown. Some pyrethroids also have strong repellency and long residual activity, making them excellent candidates for preventive management of certain insects. They are also stable in water, soil, and under sunlight.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(3A) bifenthrin, cyfluthrin, cyhalothrin, cypermethrin, deltamethrin, fenpropathin, tau-fluvalinate, permethrin, *pyrethrins**

How the Chemistry Works Within the Pest

Pyrethroids disrupt sodium/potassium ion equilibrium along nerve cell membranes. Pyrethroids hold sodium channels open and allow more sodium ions to flow into the nerve cell, which causes repeated nerve impulses and excessive excitation.

How You Might Observe that Treatments are Working

Affected arthropods may twitch after initial knockdown, then muscles become paralyzed causing energy depletion and death.

General Notes on Target Arthropods

Pyrethroids have broad-spectrum activities against sucking (e.g., aphids, whiteflies, mealybugs, plant bugs, thrips, etc.) and chewing insects (e.g., beetles and caterpillars). Pyrethroids can also be used as effective preventive sprays against wood-boring insects and leafminers. Although labeled, the efficacy of pyrethroids against mites is typically mediocre.

Interactions with Non-Target Arthropods

Broad-spectrum pyrethroids can have significant detrimental effects on survival of non-target arthropods like predatory insects and mites, parasitoids, pollinators and soil decomposers. Disruption of natural biological control by pyrethroids may result in increased infestation and outbreaks of some pests (e.g., scale insects). Pyrethroids should not be applied when pollinators are foraging. Long lasting soil residual activity of fipronil can result in death of aquatic insects if treated soil is carried with groundwater into ponds and streams.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

Additional Notes for Optimal Deployment

Pyrethroids are contact insecticides; therefore, thorough coverage of the plants should be achieved for maximum efficacy. The applications of pyrethroids are not effective against concealed pests, such as larvae of wood-boring insects and leafminers; therefore, thorough topical applications on the trunks or leaves to prevent the entry of these insects (adults or larvae) are crucial to successful control.

Origin and History

Pyrethrins are natural organic compounds extracted from pyrethrum plants (*Chrysanthemum cinerariaefolium* and *C. coccineum*). These compounds have been used since 400 B.C. The first synthetic pyrethroid, allethrin, was developed by the USDA in 1949 as modified chemical forms of naturally occurring pyrethrum. To date, as many as 45 pyrethroids have been developed. Of these, nine are frequently deployed by the turf and ornamental industry for both professional and homeowner uses.

Within this Mode of Action, subgroup 3B compounds historically included DDT and methoxychlor. Dichlorodiphenyltrichloroethane (DDT), discovered in 1873, is another sodium channel modulating insecticide. Although formerly considered an organochlorine (Group 2), current IRAC classification places this pesticide in Group 3. DDT was widely used during and after World War II and hailed as a significant contributor to improving human health. However, DDT also gained considerable notoriety for its long-lasting deleterious environmental impacts. Registered uses of DDT in the U.S. were cancelled, and the compound was banned in 1973. Methoxychlor was registered as a pesticide alternative to DDT in 1948. Concerns about its toxicity and environmental persistence led to the 2003 cancellation of all methoxychlor registered uses and products.

Current Status

Pyrethroids are the workhorses of the green industry. Hundreds of products and formulations are currently available. Due to extensive use of this chemical class, resistance to pyrethroids has been reported in many insect species, including many flies, mosquitos, leafminers, southern chinch bug and bluegrass weevil. To delay development of resistance and to prolong the effectiveness of pyrethroids, a resistance management program must be actively employed. **Many pyrethrin products have been removed or withdrawn from registered uses in homeowner or residential markets.*

GROUP 4 INSECTICIDE

GROUP MODE OF ACTION

Nicotinic acetylcholine receptor competitive modulators

IRAC CHEMICAL SUBGROUPS[1]

Neonicotinoids (4A); *Nicotine* (4B);* Sulfoximines (4C); Butenolides (4D)

General Group Profile

Neonicotinoids are systemic and may have high water solubility or less likelihood of binding to lipids. Compounds are absorbed by plant roots, leaves and stem or trunk tissues, and then transported to the branches and leaves via the vascular system. The speed at which the active ingredient is absorbed is the fastest in dinotefuran, followed by thiamethoxam, acetamiprid, imidacloprid and clothianidin. Insects then ingest neonicotinoids in plant sap and die. Sulfoxaflor is also a systemic compound, however, its speed of translocation is much slower than the neonicotinoids. Sulfoxaflor is typically tightly bound to organic matters in the soil or potting medium, making it unavailable for absorption; therefore, soil drench application of sulfoxaflor is not allowed on the label. Flupyradifurone has good systemic activity and is labeled for both foliar and drench applications. Nicotine is a botanical extract, acetamiprid is a pyridylmethylamine neonicotinoid, while clothianidin, dinotefuran, imidacloprid and thiamethoxam are nitroguanidine neonicotinoids, sulfoxaflor is a sulfoximine compound, and flupyradifurone is a butenolide compound.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(4A) acetamiprid, clothianidin, dinotefuran, imidacloprid, thiamethoxam; (4C) sulfoxaflor; (4D) flupyradifurone

How the Chemistry Works Within the Pest

Neonicotinoids, sulfoxaflor and flupyradifurone are acetylcholine mimics that permanently bind to nicotinic acetylcholine receptors and effectively blocking nerve transmission. These compounds are insensitive to degradation by acetylcholinesterase, so nerve impulses are transmitted rapidly and uncontrollably.

How You Might Observe that Treatments are Working

In treated insects, persistent activation of the nervous system leads to hyper-excitation, convulsions, lethargy, paralysis and eventually death. To determine scale insect viability, flip them over and examine the color of the bodies – if they are brown or black and desiccated, the insects are dead.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products. Italicized A.I.s followed by an asterisk may no longer be available commercially.

General Notes on Target Arthropods

Systemic insecticides are often used to control sucking insects that feed on the phloem, including aphids, whiteflies, scale insects and mealybugs. Even when the pests hide in hard-to-reach places or have thick waxy deposits or shells that hinder the penetration of contact insecticide, they still ingest the insecticide when sucking on plant sap. Neonicotinoids also have activity against beetles and thrips that are feeding on the foliage (see labels for specific groups or species). Sulfoxaflor is currently labeled for uses against sucking insects (aphids, whiteflies, mealybugs, plant bugs and some scale insects), thrips and other pests. Flupyradifurone is labeled for the management of sucking insects (listed above, as well as leafhoppers and psyllids) and thrips.

Interactions with Non-Target Arthropods

Nicotine and nicotine sulfate have serious environmental and health risks due to low efficacy against insects and high toxicity to mammals. About 60 mg (or 2/1000 oz) of pure nicotine is lethal to an average adult human. Due to the high mammalian toxicity of nicotine, there are no nicotine products labeled for legal use as insect controls. Extracts cannot be recommended for use as organic insect control solutions. As chlorinated analogs of nicotine, neonicotinoids are much less toxic to mammals than nicotine. However, neonicotinoids can still have detrimental impact on the survival of some natural enemies and pollinators, particularly when applied as foliar applications. Acetamiprid has lower toxicity to honey bees than clothianidin, dinotefuran, imidacloprid and thiamethoxam. Additional studies on the effects of sulfoxaflor and flupyradifurone on non-target organisms are being conducted.

Additional Notes about the Systemic Activity and Use of Neonicotinoids

Neonicotinoids differ significantly among the active ingredients in their water solubility and mobility. Plant tissues translocate dinotefuran more readily than clothianidin, imidacloprid and thiamethoxam, allowing faster activity against target pests in tree canopy by dinotefuran. Acetamiprid, which binds tightly to soil, is not registered for soil drench, soil injection or granular application. New application methods, such as granular formulations, directed sprays to lower trunk sections, pellets, and soil injection methods, have been developed for some neonicotinoid products. Recent studies suggested that the choice of application method does not influence the efficacy of the neonicotinoids. The efficacy is, however, influenced by the scale insect groups, feeding locations and life stages. Neonicotinoids generally do not have high efficacy against armored scales, adult female scales and those species that feed on woody host plant tissues.

Additional Notes on Pollinator Conservation When Using Neonicotinoids

Neonicotinoids, when applied as foliar applications, can have detrimental effects on the survival and functions of beneficial insects and pollinators, including honey bees, bumble bees and native (solitary) bees. Drench application to flowering plants can also cause elevated risks to pollinators that feed on pollen and nectar. Labels of nitroguanidine neonicotinoid insecticides include prominent bee advisory box, which provides a clearly statement about potential impacts of the insecticide to bees and other pollinators, and direct the applicators to read the application restrictions listed on the label. Labels of acetamiprid (a pyridylmethylamine neonicotinoid), sulfoxaflor and flupyradifurone products do not currently contain bee advisory box.

Origin and History

Water extracts of tobacco containing nicotine have been used for garden insect control as early as 1690. Discovery and research on neonicotinoids began in the 1970s. Imidacloprid was discovered in 1985 and commercialized in 1994. Acetamiprid, clothianidin, dinotefuran and thiamethoxam neonicotinoids were introduced to the turf and ornamental industry after 2000. Although the chemical group in which sulfoxaflor belongs is known to the chemists in 1940s, research for insecticidal properties of this compound did not begin until late 2000s. Dow AgroSciences introduced sulfoxaflor (in a combination product with spinetoram of IRAC Group 5) to the ornamental market in 2014. Sulfoxaflor was de-registered from the ornamental market in 2015 due to litigation over concerns about its impact on pollinator health, but the product was re-registered and reintroduced by Corteva in 2019. Flupyradifurone is a result of chemical modification of a natural occurring plant compound, stemofoline, and was developed in the mid-1990s through early 2000s. Bayer Crop Science introduced flupyradifurone to the ornamental market in 2017.

Current Status

Similar to carbamates, organophosphates and pyrethroids, neonicotinoids have been some of the most extensively used chemicals in the green industry. A large number of products and formulations containing neonicotinoids, and products that combine neonicotinoids with pyrethroids or other chemicals, are available for the green industry. Neonicotinoids and other insecticides, when used in violation of label instructions, can cause significant detriment to the survival and health of individual pollinators and their colonies (*see above*). Applicators of insecticides and their supervisors are advised to follow label restrictions and precautions faithfully. Sulfoxaflor is currently available to the ornamental industry as a combination product formulated to include spinetoram. Flupyradifurone is currently available for the management of insect pests on ornamental plants grown in landscape, greenhouses and nurseries.

GROUP 5 INSECTICIDE

GROUP MODE OF ACTION

Nicotinic acetylchlorine receptor allosteric modulators – Site I

IRAC CHEMICAL SUBGROUPS[1]

Spinosyns

General Group Profile

Spinosyns have contact and ingestion activity against a wide range of chewing and sucking insect pests. Target pests often stop feeding and moving within hours of contact with insecticide residue, and they die soon after contact. The activity of spinosyns is greater against larvae than it is against adults. Spinosyns have no systemic activity.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

spinosad, spinetoram

How the Chemistry Works Within the Pest

Spinosyns disrupt binding at the nicotinic acetylchlorine receptors causing prolonged stimulation of the nervous system. In contrast to neonicotinoids, which bind directly to the receptors, spinosyns affect receptors allosterically, i.e., by binding to the Da6 subunit and changing the shape of the nicotinic acetylchlorine receptor, which affects the ability of the receptor to bind perfectly to the acetylcholine molecules. Spinosyns are also antagonistic to GABA-gated ion channels.

How You Might Observe that Treatments are Working

Treated insects are first hyper-excited, then become paralyzed leading to death.

General Notes on Target Arthropods

Spinosyns are highly effective against caterpillars, leafminers, beetles and thrips. Additional target pests include whiteflies, fungus gnats, shore flies and fire ants. Efficacy against spider mites is relatively low.

Notes on Interactions with Non-Target Arthropods

Spinosad and spinetoram have low environmental and mammalian toxicology profiles, so is registered by EPA as a reduced risk insecticide. Spinosad, when sprayed, is toxic to parasitic wasps and bees but has less effect on ladybeetles, lacewings and predatory bugs.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

Additional Notes for Optimal Deployment

Spinosyns do not have systemic activity, therefore, thorough coverage of the plant canopy is recommended. These chemicals are also more effective against larvae than adults. Careful timing of application is therefore recommended so the insecticide is applied during the most vulnerable life stage or developmental time during a target pest's life cycle. For target pests with overlapping generations, repeated applications or (preferably) rotation with another MOA is highly recommended.

Origin and History

In 1986, Eli Lilly scientists identified spinosad as a fermentation byproduct produced by *Saccharopolyspora spinosa,* which is an actinomycete bacterium. The bacterial strain used to produce spinosad was found in 1982 in an abandoned rum distillery on the British Virgin Islands. Two major metabolites of *S. spinosa*: spinosyn A and spinosyn D, are responsible for the insecticidal activity. The name 'spinosad' is derived by combining *spinosa* with A and D metabolites. The same fermentation products that yielded spinosad were further developed and modified, resulting in the discovery of spinetoram by Dow AgroSciences. Because of the artificial molecular structural modifications, spinetoram is considered 'semi-synthetic.' Spinetoram is registered in the U.S. in 2007 under EPA's Reduced Risk Pesticide Initiative. Spinetoram was introduced in a combination product with sulfoxaflor (IRAC Group 4C) by Dow AgroSciences (now Corteva) to the ornamental industry in 2014.

Current Status

Spinosad is generally considered an organic insecticide because it is a product of fermentation, and some products have been approved for use on certified organic produce. The intensity and frequency of the use of spinosad has led to the development of resistance in some regions of the U.S. In late 2008, Dow AgroSciences suspended the sale and use of spinosad in Broward and Palm Beach County, Florida due to resistance development in western flower thrips. Dow introduced spinetoram (in a combination product with sulfoxaflor) to the ornamental industry in 2014.

GROUP 6 INSECTICIDE

GROUP MODE OF ACTION

Glutamate-gated chlorine channel allosteric modulators

IRAC CHEMICAL SUBGROUPS[1]

Avermectins, Milbemycins

General Group Profile

Abamectin and milbemectin have contact and translaminar activity. Translaminar activity provides a measure of control against mites feeding on the underside of leaf or leafminers feeding between leaf epidermises even if only upper leaf surfaces are treated. Emamectin benzoate has systemic activity, which allows this compound to be formulated for trunk injection for controlling wood boring insects and sucking insects in urban landscapes.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

abamectin, emamectin benzoate, *milbemectin**

How the Chemistry Works Within the Pest

Thought to be blockers of the GABA receptor, avermectins and milbemycins are now known to induce opening of glutamate-gated chlorine channels of nerve cell by changing the shape of the receptor (thus allosterically). When the compounds attach to the receptor, the chlorine channel is activated and chlorine ions continue to flow into the nerve cells, resulting in continuous excitation of the nervous system.

How You Might Observe that Treatments are Working

Prolonged opening of the chlorine channels leads to convulsion, paralysis and death.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products. Italicized A.I.s followed by an asterisk may no longer be available commercially.

General Notes on Target Arthropods

Abamectin is effective against immature and adult spider mites, eriophyid mites, broad mite and cyclamen mite (eggs are generally not killed), thrips, whiteflies and leafminers. Certain abamectin products are also registered for the management of plant parasitic nematodes.

Interactions with Non-Target Arthropods

Although this group of chemicals has a low mammalian toxicity, their toxicity to fish and aquatic invertebrates is high. Label instructions regarding site restrictions and buffer zones should be followed. This group of compounds is generally not compatible with entomopathogenic nematodes, or small, soft-bodied biological control agents, such as predatory mite species, parasitoids and minute pirate bugs. Compounds have better compatibility profiles with larger, more robust biological control agents including ladybeetles and lacewing larvae. Check with biological control agent suppliers for more details.

Origin and History

The actinomycete bacteria, *Streptomyces avermectinius*, was isolated from soil samples collected in 1978 at Ito City, Japan. Lab assays with the active ingredient avermectin, which was recovered from fermentation broth in which the bacteria were cultured, demonstrated showed insecticidal activity. Abamectin is a mixture of avermectin B1a and B1b. Emamectin benzoate is a benzoate salt derivative of abamectin that was introduced to the green industry in 2014. Milbemycins are the metabolites of fermentation by *Streptomyces hygroscopius*, a species discovered in the soil of Hokkaido, Japan.

Current Status

Several insecticides, nematicides and fire ant baits containing abamectin are currently registered for the green industry. Milbemectin is no longer available to the ornamental industry.
Trunk injection of emamectin benzoate is effective at managing the invasive emerald ash borer.

GROUP 7 INSECTICIDE

GROUP MODE OF ACTION

Juvenile hormone mimics

IRAC CHEMICAL SUBGROUPS[1]

Juvenile hormone analogues (7A);
Fenoxycarb (7B); Pyriproxyfen (7C)

General Group Profile

Juvenile hormone (JH) mimics are insect growth regulators that have broad-spectrum activity against many pest species because the target process (i.e. metamorphosis) of these compounds is synthesized naturally by insects and crucial to their developmental processes.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(7A) s-kinoprene, s-methoprene; (7B) *fenoxycarb**; (7C) pyriproxyfen

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How the Chemistry Works Within the Pest

JH mimics kill insects by modifying or stopping the development of immature insects, or by stopping adult reproduction. Most commonly, JH mimics disrupt metamorphosis, molting, and exoskeleton formation.

How You Might Observe that Treatments are Working

Insects exposed to JH mimics at a vulnerable developmental stage (usually as larvae) may stop feeding and maturing and can develop a mixture of larval/pupal or larval/adult characteristics that generally leads to quick death.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products. Italicized A.I.s followed by an asterisk may no longer be available commercially.

General Notes on Target Arthropods

Methoprene is effective against imported fire ants and other nuisance ants. Another JH mimic, s-kinoprene is very effective against soft-bodied sucking insects, including aphids, whiteflies, and mealybugs. Pyriproxyfen is used to control whiteflies, scale insects, mealybugs and leafminers on indoor and outdoor ornamental plants.

Notes on Interactions with Non-Target Arthropods

JH mimics have low mammalian toxicity and high environmental safety, due in part, to their specificity against insects. These products are therefore classified as reduced risk pesticides by the U.S. EPA. JH mimics have low toxicity to many beneficial arthropods, including predatory mite, parasitoids, ladybeetles, and minute pirate bugs; thus, they are ideal for inclusion into an IPM program. However, because of potential impact on immature biological control agents, JH mimics should be used carefully when the biological control program is heavily reliant upon immature predators (such as lacewing larvae).

Additional Notes for Optimal Deployment

JH mimics disrupt normal development and consequently must be applied against immature life stages. Therefore, careful timing of the application is crucial to the success of the management programs. Recent studies suggest that repeated applications of pyriproxyfen timed to control the crawlers (i.e., the hatchlings) are effective in managing some hard-to-control armored scale species on ornamental trees and shrubs.

Origin and History

Insect growth regulators (IGRs), including JH mimics, were developed in the 1960s as replacements for organophosphates and carbamates, which have high mammalian toxicity and environmental concerns. Methoprene was the first juvenile hormone analogue marketed in the U.S. Fenoxycarb is no longer available to the green industry in the U.S.

Current Status

Pyriproxyfen and s-methoprene are formulated as fire ant baits for use in turf and fire and quarantine treatment in nurseries. Spray formulations of pyriproxyfen can be used to control various pest species on indoor and outdoor ornamental plants. S-methroprene is currently only available for use on ornamental plants in greenhouses and interiorscapes.

GROUP 8 INSECTICIDE

GROUP MODE OF ACTION

Miscellaneous non-specific (multi-site) inhibitors

IRAC CHEMICAL SUBGROUPS[1]

Fluorides (8C); Borates (8D)

General Group Profile

Generally considered an inorganic insecticide, cryolite is a fluoride salt. It is a stable chemical that does not evaporate but can dissolve quickly in water to enable topical applications. Cryolite becomes active through ingestion. This compound has relative short residual longevity and low toxicity to non-target organisms, including mammals. Typically, multiple applications at high application rates are needed to achieve sufficient control of the target pests. Borax (boric acid and boron- or borate-containing salts) is generally considered an inorganic pesticide. It is a low toxicity mineral that does not volatilize easily. Borax has a broad range of activity against insects, fungi and weeds. This is a group of very slow acting general pesticides. As insecticides, borax acts through ingestion and as a disruptor of insect water balance.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(8C) sodium aluminofluoride (= cryolite); (8D) sodium tetraborate decahydrate

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How the Chemistry Works Within the Pest

The exact target site and protein, and thus the mode of action, of cryolite and borax are unknown. Once ingested, cryolite disassociates and releases the fluoride ions. The fluoride ions inhibit many iron-, calcium- and magnesium-containing enzymes that are involved in energy production in cells. It is generally believed that borax kill insects in two ways. First, borax is a stomach poison. When formulated as baits, borax can be ingested by insects. Once inside the insect body, borax interferes with the normal functions of enzymes or physiological processes. Borax can also be formulated as topical sprays. Once the spray solution covers the arthropod body, borate in the solution begins to absorb insect cuticular waxes. With the loss of the protective waxy layer on the cuticle, insects quickly begin to lose water and eventually die from desiccation.

How You Might Observe that Treatments are Working

Insects will slowly die following ingestion of cryolite. Insects coated by borax often convulse or twitch. Death often occurs within a day.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Cryolite is used to control leaf-feeding beetles and caterpillars on ornamental and shade trees in the landscape. Borate-containing products have a broad spectrum of pesticidal activity. Most products are registered as general pesticides and have activity against insects, mites, diseases and other pests. Registered target pests include soft-bodied insects, such as aphids, mealybugs, whiteflies, scale insects, psyllids, plant bugs, leafhoppers, mites, thrips and caterpillars.

Notes on Interactions with Non-Target Arthropods

Cryolite, once dried, is generally considered harmless to non-target organisms and biological control agents. Borax is safe to mammals so long as dusts used for household applications do not become airborne. The compatibility of borax with biological control agents and pollinators is not well known. It is advisable not to spray borax solution directly onto a population of desirable organism.

Additional Notes for Optimal Deployment

Because borax does not have residual toxicity, repeated topical applications are recommended.

Origin and History

Cryolite, used as an ore of aluminum, was first registered as an insecticide in the U.S. in 1957. Boric acid was used extensively for control of cockroaches and crawling household pests during the 1930s and 1940s. After a long period of inactivity, several additional borate-containing pesticides were registered in 1980s and 1990s.

Current Status

The predominant uses of cryolite are for the management of leaf-feeding insects on grapes, potatoes and citrus; uses on ornamental plants are rare. Few cryolite- or borate-containing products are registered for uses on ornamental plants.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

GROUP 9 INSECTICIDE

GROUP MODE OF ACTION

Chordotonal organ TRPV channel modulators

IRAC CHEMICAL SUBGROUPS[1]

Pyridine azomethine derivatives (9B);
Pyropenes (9D)

General Group Profile

These compounds affect nervous system functions associated with balance, positioning and behavior of insects. Insects often become disoriented or unable to move or feed properly within hours of application. Insecticides in this IRAC Group have translaminar activity; some such as pymetrozine have systemic activity.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(9B) pymetrozine, pyrifluquinazon; (9D) afidopyropen

How the Chemistry Works Within the Pest

Chordotonal organs are sensory organs located at the joints and between body segments of insects. These structures are responsible for sensing the position of body segments relative to each other. By sensing the relative positions of joints and segments, an insect is able to detect vibration, pressure and gravity, which in turn affect the responses of the insect to these stimuli through behavioral and physiological processes. Chordotonal organ Transient Receptor Potential Vanilloid (TRPV) channel modulators bind with TRPV channel gates, causing continue stimulation and eventually silencing TRPV channel processes. Disruption of normal flows of sodium and potassium through the TRPV channel also affects the generation of nerve impulses.

How You Might Observe that Treatments are Working

Intoxicated insects become unable to move or fly normally. The first sign of poisoning appears within hours of application as the insects' inability to land or hang onto host plants; they may drop from host plant tissues and surfaces. Affected insects are unable to feed or move and will die during the next 36-40 hours.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Chordotonal organ TRPV channel modulators target primarily sucking insects, such as aphids, whiteflies and mealybugs. Pyrifluquinazon also has efficacy against thrips.

Notes on Interactions with Non-Target Arthropods

The highly specific activity against sucking pests results in low lethal or sub-lethal activity to predators and parasitoids used in biological control programs, as well as limited ecotoxological profiles.

Additional Notes for Optimal Deployment

Although all chordotonal organ TRPV channel modulators have translaminar activity, the products should be applied to achieve full coverage of the canopy. Pymetrozine is also registered for soil drench application, which should be applied before the pest population appear or build up.

Origin and History

Developed in the 1980s, pymetrozine was introduced to the ornamental market by Syngenta in 1999. Pyrifluquinazon was developed by Nihon Nohyaku Co. Ltd. in Japan in 2010, and was introduced to the U.S. ornamentals market by SePRO in 2014. Developed in early 2010s, afidopyropen was introduced to the ornamental market by BASF in 2019.

Current Status

Pymetrozine, pyrifluquinazon and afidopyropen are currently available for management of sucking insects in greenhouses, interiorscapes, nurseries and landscape ornamentals. All products are registered for use as foliar sprays, but only pymetrozine is registered to be applied as a media drench.

GROUP 10 INSECTICIDE

GROUP MODE OF ACTION

Mite growth inhibitors affecting CHS1

IRAC CHEMICAL SUBGROUPS[1]

Clofentezine, Hexythiazox, Diflovidazin (10A); Etoxazole (10B)

General Group Profile

As mite growth regulators, clofentezine, hexythiazox and etoxazole affect only eggs and immature spider mites, with no direct effect on adult mites. However, eggs deposited by adult mites will be non-viable. These are contact miticides that have long residual activity (28-45 days).

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(10A) clofentezine, hexythiazox; (10B) etoxazole

How the Chemistry Works Within the Pest

Mite growth inhibitors interfere with chitin synthesis during the molting process. These miticides interfere with the normal functioning of chitin synthase 1 (CHS1) and result in the inhibition of production and polymerization of chitin, which is a major component of the insect cuticle. Both embryo development and larval maturation can be disrupted.

How You Might Observe that Treatments are Working

Because mite growth regulators work through the developmental processes of spider mites, these products do not cause quick knockdown of the mite population. Instead, molting and metamorphosis are disrupted and mites will begin to die a few days after the application.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Products containing these three chemistries are contact miticides that provide efficacy against eggs and immature life stages of spider mites. These products have low to no efficacy against broad, cyclamen and eriophyid mites. Some products are also labeled for suppression of other insect pests, such as whitefly by etoxazole.

Notes on Interactions with Non-Target Arthropods

These miticides are spider mite-specific; therefore, they are compatible with many predatory mites, including many species of the family Phytoseiidae that are used for biological control. Impacts on other predators, parasitoids, invertebrates and mammals are also limited.

Additional Notes for Optimal Deployment

These miticides have only contact activity; therefore, complete and even coverage of all plant surfaces is very important to achieve successful control. Since the products are more effective against eggs and larvae that emerged during the effective residual period, application should be conducted as early in the infestation process as possible. In situations of mixed life stages, another miticide with activity against adults may have to be applied before the mite growth inhibitors or used in a tank mix.

Origin and History

Development of clofentezine, hexythiozox and etoxazole began in the mid- to late-1980s. Market commercialization occurred in the early to late 1990s.

Current Status

Currently, clofentezine, etoxazole and hezythiazox are available for control of spider mites in indoor and/or outdoor areas.

GROUP 11 INSECTICIDE

GROUP MODE OF ACTION

Microbial disruptors of insect midgut membranes

IRAC CHEMICAL SUBGROUPS[1]

Bacillus thuringiensis (*Bt*) and the insecticidal proteins they produce (11A)

General Group Profile

Bacillus sphaericus and *Bt* subspecies *israelensis* are primarily used for biological control of mosquito, blackfly, biting fly and midge larvae in lakes, ponds, marshes and other natural or artificial water bodies. Currently, products containing *Bacillus sphaericus* (IRAC 11B) are not available to the ornamental industry; therefore, these products will not be discussed in this publication. *Bt* requires ingestion of the bacterial spores or proteins by the target pests to be effective. *Bt* is also more effective against immature insects than adults.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(11A) *Bacillus thuringiensis* (*Bt*) subspecies *aizawai*, *Bt* subsp. *galleriae*, *Bt* subsp. *israelensis*,

Bt subsp. *kurstaki*, *Bt* subsp. *tenebrionensis*

How the Chemistry Works Within the Pest

Insecticidal properties of *Bt* are not due to direct pathogenicity (*i.e.,* causing diseases in insects), but are affected by release, upon ingestion, of crystal delta-endotoxins (or *Cry* proteins), that are produced by these bacteria. Within the insect digestive tract, the alkaline pH and insect's gut enzymes degrade the crystals into their three constituent components, thus activating the endotoxins. The central domain binds to receptor sites on insect midgut membranes and forms porous cation channel that disrupts the potassium ion and pH balances on either side of the membrane. The rise of pH in the blood (haemolymph) of insects results in paralysis and eventual death of the insect.

How You Might Observe that Treatments are Working

Insect larvae stop eating. Leakage of midgut fluids into the body results in bacterial infection. Larvae become lethargic then limp.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Each *Bt* subspecies has targeted specificity to a select group of insects, so it is important to know the target pest and the effective control spectrum for individual *Bt* products. *Bt* subsp. *israelensis* controls fungus gnats and other flies and midges, whereas *Bt* subsp. *aizawai* and *Bt* subsp. *kurstaki* target caterpillars. *Bt* subsp. *tenebrionensis* is only effective against beetle larvae, and *Bt* subsp. *galleriae*, which is currently not listed by IRAC, is registered for management of white grubs in turf.

Notes on Interactions with Non-Target Arthropods

Because of their high level of target specificity and an absence of toxicity against human and other animals, *Bt* products are used as biological control agents, considered environmentally friendly, and accepted by all organic certification programs. *Bt* is compatible with all commercially available biological control agents.

Additional Notes for Optimal Deployment

Most *Bt* products are formulated as granules, baits, pellets or briquettes, while some can be applied as foliar spray solutions. *Bt* products are only effective against actively feeding insects and product efficacy decreases as insects mature and grow larger. Reapplications of products containing *Bt* are often necessary within 1-4 weeks as the products break down and lose efficacy. Because formulated products may contain live bacteria and spores, it is important to follow label directions regarding storage, particularly in avoiding exposure to direct sunlight and high temperatures.

Origin and History

Bt was first discovered in 1902 by Japanese biologist Shigetane Ishiwatari and described in 1911 by German scientist Ernst Berliner. *Bt* naturally occurs in the soil, on leaf surfaces, and within ground- and standing-water. Insecticides containing spores or endotoxins of *Bt* were introduced in the 1920s. In 1976, the *cry* gene was detected within the circular string of DNA in the bacterial plasmid and determined to be responsible for endotoxin production. Many other *Cry* proteins and *cry* genes are now known. In 1985, *cry* genes were isolated and inserted into plant genes, after which, the genetically modified (GM) plants produce the endotoxins or *Cry* proteins just like *Bt* bacteria. *Bt*-corn and cotton have been widely planted since 1996. Products containing *Bacillus sphaericus* (11B) are used against mosquito control, yet do not have labels that permit application in ornamental use sites.

Current Status

Many *Bt* subsp. *aizawai* and *Bt* subsp. *kurstaki* products are registered for caterpillar management in agricultural, commercial and residential settings. *Bt* subsp. *isrealensis* is registered for fungus gnat and shore fly management in greenhouses, interiorscapes and nurseries, whereas *Bt* subsp. *tenebrionensis* is registered for elm leaf beetle control on shade and ornamental trees. *Bt* subsp. *galleriae* is currently registered for management of white grubs in turfgrass and scarab beetles (such as Japanese beetle) on ornamental plants.

GROUP 12 INSECTICIDE

GROUP MODE OF ACTION

Inhibitors of mitochondrial ATP synthase

IRAC CHEMICAL SUBGROUPS[1]

Organotin miticides (12B)

General Group Profile

Fenbutatin-oxide generally has low acute and chronic mammalian toxicities and non-carcinogenic to human. However, it is known to be a severe eye irritant (therefore, considered by EPA to be of high acute toxicity) and highly toxic to aquatic organisms. Thus, fenbutatin-oxide is registered as a restricted use pesticide.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(12B) fenbutatin-oxide (a.k.a. hexakis)

How the Chemistry Works Within the Pest

Plants and animals have hundreds of mitochondria maintained within in each individual cell. Mitochondria convert chemical energy released during nutrient breakdown into cellular energy, in the form of adenosine triphosphate (ATP). This metabolic process, called oxidative phosphorylation, occurs within the innermost matrix of a mitochondrion. ATP is then transported throughout the body for used in many physiological functions. Fenbutatin-oxide works by inhibiting the actions of ATP synthase and disrupting the production of ATP.

How You Might Observe that Treatments are Working

Although highly effective and with long residual toxicity (about 30 days), organotin miticides usually cause mortality across a period of several days.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Fenbutatin-oxide is currently registered for control of spider mites (twospotted, southern red, spruce, oak mites) and clover mite in greenhouses, nurseries and landscapes.

Notes on Interactions with Non-Target Arthropods

Fenbutatin-oxide is compatible to predatory mites, ladybeetles, lacewings, minute pirate bug and other biological control agents. Fenbutatin-oxide is practically nontoxic to bees when the spray solution has dried. The compound is considered highly toxic to fish, aquatic invertebrates, birds and mammals; therefore, avoid using the product near water or where runoff is likely to occur.

Additional Notes for Optimal Deployment

Fenbutatin-oxide is a contact miticide. Thorough coverage of the canopy is required for an effective treatment. Fenbutatin-oxide performs better at higher temperature. Application of fenbutatin-oxide should only be made when the temperature at the time of application is above 70 F.

Origin and History

The fungicidal, acaricidal, insecticidal and molluscidal activities of organic compounds of tin were discovered in the 1950s. Fenbutatin-oxide is an organotin miticide first developed in the 1960s. EPA granted registration of fenbutatin-oxide miticide in 1974.

Current Status

Currently, fenbutatin-oxide is available as a restricted use miticide registered for uses on ornamental plants in greenhouses, nurseries and landscape. Fenbutatin-oxide is often formulated in water-soluble packages to reduce exposure to workers during handling and mixing. Resistance to fenbutation-oxide has been reported in twospotted spider mite populations in outdoor fruit production. Resistance in ornamental production has not been reported.

GROUP 13 INSECTICIDE

GROUP MODE OF ACTION

Uncouplers of oxidative phosphorylation via disruption of the proton gradient

IRAC CHEMICAL SUBGROUPS[1]

Pyrroles

General Group Profile

Chlorfenapyr, a member of the chemical class pyrroles, is a pro-insecticide (i.e., an insecticide that become active only after entering the insect body). Because insects and mites use similar oxidative phosphorylation process, this group of insecticides often has efficacy against both mites and insects.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

chlorfenapyr

How the Chemistry Works Within the Pest

Oxidative phosphorylation is the process by which mitochondria produce cellular energy from nutrient breakdown (*see Group 12*). Once inside an insect's body, chlorfenapyr is converted to the biologically active compound CL 303268. CL 303268 disrupts the proton gradient that is essential to normal functioning of oxidative phosphorylation across the mitochondrial matrix, which disconnects the actions of the electron transport chain. As a result, the production of ATP is inhibited.

How You Might Observe that Treatments are Working

Mortality typically occurs within 72 hours of application.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Target pests include spider mites, broad mite, cyclamen mite, rust mite, caterpillars, fungus gnats and thrips, as well as foliar nematodes on greenhouse-grown plants.

Notes on Interactions with Non-Target Arthropods

Chlorfenapyr is not registered for outdoor uses because of concerns over its high reproductive toxicity against birds. Exposure to birds and other wildlife is low or nonexistent when the compound is used in the greenhouses. Based on current research, chlorfenapyr has inconsistent effects on the survival of various groups of biological control agents. For example, survival of the predatory mite *Phytoseiulus persimilis* may be reduced while other predatory mites (e.g., *Neoseiulus californicus*) may persist. Others reported that chlorfenapyr was highly toxic to *P. persimilis* adults, *Encarsia formosa* adults and *Macrolophus caliginosus* larvae, while the impact on *Orius laevigatus* larvae and *E. formosa* pupae was minimal. Additional studies are needed before we can reach a conclusion on the compatibility of chlorfenapyr with biological control agents. But, it is generally recommended that chlorfenapyr should not be integrated into biological control programs.

Additional Notes for Optimal Deployment

Although chlorfenapyr has both translaminar and contact activities against immature and adult mites and insects, thorough coverage of the entire plant is still recommended for successful management. Chlorfenapyr has limited efficacy against eggs; therefore, another miticide with ovicidal activity should be included in the tank mix or rotation program. Alternatively, make a second application 5-7 days later to target nymphs that have hatched from the unaffected eggs.

Origin and History

Chlorfenapyr was discovered as a toxin produced by the actinomycete bacterium *Streptomyces fumanus* in 1985. American Cyanamid (now BASF Ag) developed the compound as an agricultural product in the 1990s. BASF registered the uses of chlorfenapyr on greenhouse-grown ornamental plants in the U.S. in 2001.

Current Status

No outdoor uses of chlorfenapyr are allowed in the U.S.

GROUP 15 INSECTICIDE

GROUP MODE OF ACTION

Inhibitors of chitin biosynthesis affecting CHS1

IRAC CHEMICAL SUBGROUPS[1]

Benzoylureas

General Group Profile

Benzoylureas are insect growth regulators that enter target pests through contact and ingestion. The compounds do not have systemic or translaminar activity in plant tissues. Because chitin biosynthesis inhibitors interfere with the molting process and only immature arthropods molt, these chemicals are most effectively against larvae and nymphs.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

diflubenzuron, novaluron

How the Chemistry Works Within the Pest

Diflubenzuron and novaluron interfere with chitin synthase 1 (CHS1), which in turn affect chitin production. The new exoskeleton of the affected insect fails to form or will form incorrectly. Protective and supportive functions are lost, leading to insect death.

How You Might Observe that Treatments are Working

Affected insects may be deformed after molting. Loss of mobility and physical functions can lead to death.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Products containing diflubenzuron and novaluron are currently labeled for management of caterpillars, whiteflies, fungus gnats, shore flies, leafminers, and thrips on ornamental plants.

Notes on Interactions with Non-Target Arthropods

Diflubenzuron and novaluron have low toxicity against many beneficial organisms used in biological control programs, including *Amblyseius* and *Hypoaspis* predatory mites, lacewings, *Eretmocerus* parasitic wasps, nematodes and entomopathogenic fungi. Application of diflubenzuron should be avoided if minute pirate bugs have been released because of high toxicity when directly sprayed.

Additional Notes for Optimal Deployment

Diflubenzuron and novaluron are insect growth regulators and should be used against immature insects. Apply to achieve uniform coverage of the foliage. When used against fungus gnats and shore flies, diflubenzuron should be applied to wet the medium surface.

Origin and History

Diflubenzuron was first discovered in 1972 and introduced in the U.S. in 1979. Additional benzoylureas were discovered during the process of optimizing and synthesizing analogues of diflubenzuron. Novaluron was discovered during the optimization process and was used as an insecticide in South Africa, Argentina and Australia before it was the labeled for the U.S. ornamental industry in 2001.

Current Status

Diflubenzuron is currently registered for uses in sod farms, whereas novaluron is registered for uses on turfgrass in sod farms, recreational turf and lawns as well as ornamental plants in outdoor nurseries, shadehouses, and greenhouses.

GROUP 16 INSECTICIDE

GROUP MODE OF ACTION

Inhibitors chitin biosynthesis, type 1

IRAC CHEMICAL SUBGROUPS[1]

Buprofezin

General Group Profile

Similar to benzoylureas, buprofezin is an insect growth regulator that does not have systemic activity in plant tissues. Target pests are exposed to buprofezin through contact, ingestion of residue, or spiracular uptake of volatilized product. Buprofezin has activity against survival of immature insects and reproduction of adult insects.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

buprofezin

How the Chemistry Works Within the Pest

Buprofezin inhibits chitin synthesis and successful deposition of chitin in forming the insect exocuticle. Insect cuticle affected by buprofezin becomes inelastic and brittle. Buprofezin also suppresses reproduction in adults or induces adults to deposit sterile eggs.

How You Might Observe that Treatments are Working

Treated insects die shortly after their next molt, often trapped within the old skin.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Type 1 chitin biosynthesis inhibitors are primarily effective against immature homopteran pests (whiteflies, mealybugs, leafhoppers, planthoppers, psyllids, soft scales, armored scales and cottony cushion scales).

Notes on Interactions with Non-Target Arthropods

Buprofezin has low toxicity against predatory mites, parasitoids, lacewing, ladybeetles and minute pirate bugs. High toxicity of buprofezin to the larvae of predatory midges (*Aphidoletes aphidimyza*) has been documented; therefore, avoid application of buprofezin in greenhouses where the predatory midges are in use for aphid management.

Additional Notes for Optimal Deployment

Because buprofezin does not directly reduce adult survival, applicators should consider tank mixing buprofezin with another chemical that has adulticidal activity, or buprofezin can be rotated with another insecticide. Repeated applications across multiple years, of a combination of horticultural oil and buprofezin, have helped suppress armored scales populations. Applications should coincide with timing of immature crawlers activity. Thorough spray coverage of the potting medium (e.g., for fungus gnat and shore fly control) and plant canopy is essential.

Origin and History

Discovery and development of buprofezin began in Japan in the 1970s and the products were first marketed in the 1980s by Nihon Nohyaku Co., Ltd. Buprofezin was used successfully in Asia to combat infestations by brown planthoppers in rice. Buprofezin was introduced to the ornamental industry in the U.S. in 2004.

Current Status

Buprofezin is currently registered for the management of homopteran pests on indoor and outdoor ornamental plants.

GROUP 17 INSECTICIDE

GROUP MODE OF ACTION

Dipteran molting disruptors

IRAC CHEMICAL SUBGROUPS[1]

Cyromazine

General Group Profile

Sometime considered a member of the insecticide class triazines, cyromazine is an insect growth regulator with a narrow specificity against fly and midge larvae.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

cyromazine

How the Chemistry Works Within the Pest

The exact mechanism by which cyromazine interferes with the biochemical processes of insect molting is unknown, but differs from the action of other chitin biosynthesis inhibitors previously mentioned. Cyromazine may interfere with the molting hormone, 20-hydroxyecdysone, or the process of chitin deposition. Larvae are poisoned after ingesting treated plant tissues and algae that are used as food resources.

How You Might Observe that Treatments are Working

Development of the fly larvae is arrested, molting is disrupted, and larvae eventually die.

General Notes on Target Arthropods

This chemical is only effective against dipteran (fly) pests, including leafminers, fungus gnats and shore flies. Most effective when used with another chemical/practice to control adult flies.

Interactions with Non-Target Arthropods

Cyromazine is compatible with predatory mites, parasitoids and predators (including ladybeetles, lacewings and minute pirate bugs) commonly used in biological control programs.

Additional Notes for Optimal Deployment

Sprays should be directed toward the surfaces where larvae feed and develop, such as leaf surface where leafminer larvae are active, and potting medium, benches and ground around production areas where fungus gnats and shore flies are active. This compound has no direct effect on adults, therefore, tank mix or rotate with another adulticidal product.

Origin and History

The insect growth regulating activity of cyromazine was described in 1980 and developed by Ciba-Geigy Ag (now Syngenta Ag). EPA's initial registration (1984) & ornamental plant uses were approved in 1990.

Current Status

Citation is currently the only product containing cyromazine that is registered for use on greenhouse, indoor and landscape ornamental plants and vegetables.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

GROUP 18 INSECTICIDE

GROUP MODE OF ACTION

Ecdysone receptor antagonists

IRAC CHEMICAL SUBGROUPS[1]

Diacylhydrazines

General Group Profile

Diacylhydrazines are also insect growth regulators with stomach and contact activity, and high efficacy against caterpillars. Compounds from this group are only effective when ingested by the caterpillars. Therefore, effective use of this chemical relies on timing applications to coincide with insect feeding activity during susceptible juvenile life stages.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

*halofenazide**, *methoxyfenozide**, tebufenozide

How the Chemistry Works Within the Pest

These compounds interfere with normal functioning of ecdysone receptors by binding to ecdysone receptors and accelerating the biochemical processes of larval molting. Repeated molting before larvae are ready and have achieved normal growth depletes resources and leads to death. Tefubenozide may also disrupt the development of ovaries in caterpillars.

How You Might Observe that Treatments are Working

Affected insects often show deformations, molt precociously, and development is delayed. This is a slow-acting insecticide; mortality may not become noticeable for days after application.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Tebufenozide is most useful for managing caterpillar species on Christmas trees and nursery-grown ornamental plants.

Notes on Interactions with Non-Target Arthropods

Because of its specificity against caterpillars, tebufenozide is very safe for humans, pets and other non-target animals. Tebufenozide is compatible with predatory mites, lacewing, predatory bug (*Macrolophus caliginosus*) and minute pirate bugs.

Origin and History

Scientists at Rohm and Hass Company discovered the first diacylhydrazine in 1983. Through additional modifications, a more potent analogue, tebufenozide, was discovered in 1986. Tebufenozide was introduced in the U.S. in 1994 and was mainly used for management of caterpillars on agricultural crops. Halofenozide was registered for management of caterpillars and white grubs in commercial turfgrass sites (including commercial lawns and grounds) in 1998, but this pesticide is no longer available.

Current Status

Tebufenozide is currently registered for uses on nursery-grown ornamental trees and shrubs.

GROUP 20 INSECTICIDE

GROUP MODE OF ACTION

Mitochondrial complex III electron transport inhibitors – QO site

IRAC CHEMICAL SUBGROUPS[1]

Hydramethylnon (20A); Acequinocyl (20B); Bifenazate (20D)

General Group Profile

Hydramethylnon is a stomach poison that is typically formulated as baits for ants and cockroaches. Mites are exposed to acequinocyl mainly through contact activity although there are also some activities through ingestion. Prior to being metabolized following contact, acequinocyl is inactive and the compound must be converted to its deacetylated metabolite for toxicity to occur. Feeding inhibition following ingestion of hydramethylnon and conversion of acequinocyl needed to activate toxicity, results in slower time to mortality of pests by both compounds.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(20A) hydramethylnon; (20B) acequinocyl; (20D) bifenazate

How the Chemistry Works Within the Pest

Pest cellular mitochondria convert chemicals in food into energy that can be used to power other metabolic processes in cells. Electrons released from digested food pass through a series of membranes within the innermost part (matrix) of a mitochondrion, then activate ionic pumps to create a proton and energy gradient. Under normal conditions, as protons reenter the mitochondrion via a protein (ATP synthase) and attempt to balance the gradient, energy in the form of adenosine triphosphate (ATP) is produced and then transported for use in other cellular functions. Group 20 (and 21) compounds inhibit the normal functions of electron transport complexes by binding to cytochromes, which are proteins that facilitate electron transport and enable reduction-oxidation reactions. Cytochrome organization within the mitochondrial electron transport complex allows electrons to be transported down the various membranes. Compounds are classified as effecting Electron Transport Complex I (Group 21), II (Group 25), III (Group 20, which includes bifenazate), or IV (Group 24), depending upon which membrane the chemical targets.

How You Might Observe that Treatments are Working

Once treated, insects and mites survive briefly, becoming less active as their existing energy resources are depleted. Bifenazate causes rapid cessation of feeding and mortality in spider mite populations.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Hydramethylnon is primarily used to manage nuisance and imported fire ants in landscapes and nurseries. Acequinocyl is mainly a contact miticide with activity against several spider mite species. Acequinocyl is effective against all life stages of mites and has residual activity that exceeds 28 days. Bifenazate is effective against various spider mite species on ornamental plants and clover mite.

Notes on Interactions with Non-Target Arthropods

Effective against spider mites, acequinocyl is compatible with other commonly used predatory mites including *Amblyseius swirskii*, *Amblyseius cucumeris*, *Neoseiuslus californicus*, and *Phytoseiulus persimilis*. Hydramethylnon is toxic to some fish species. Acequinocyl is toxic to aquatic invertebrates. Read product labels carefully and adhere to restrictions on chemigation, buffer zone, drift and runoff, and equipment cleaning procedures. Bifenazate is compatible with many biological control agents, including parasitoids, predatory bugs, predatory midges, ladybeetles and lacewings. Bifenazate is compatible with *Amblyseius* spp. predatory mites, but has moderate toxicity to *P. persimilis*, which is one of the most commonly used biological control agents used against spider mites.

Additional Notes for Optimal Deployment

Ant baits containing hydramethylnon should be applied when ants are foraging. Avoid application just before rain or irrigation. For effective control of spider mites by acequinocyl and bifenazate, good spray coverage on treated plant portions is essential.

Origin and History

Hydramethylnon was developed by DuPont in 1975 and introduced to ornamentals industry in the 1990s. Acequinocyl was also discovered by DuPont in the 1970s and further developed by Agro-Kanesbo Co. Ltd. and Tomen Agro in Japan. Arysta LifeScience first introduced acequinocyl to the U.S. ornamentals market in 2005. Bifenazate was first developed by Uniroyal Chemical in 1990 and commercialized by Crompton Corporation in 1999. Bifenazate was introduced to the ornamental market in 2010.

Current Status

Several ant baits containing hydramethylnon are available for landscape and nursery uses to manage imported fire ants and other nuisance ants. Acequinocyl and bifenazate are registered for uses in landscapes, greenhouses and nurseries.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

GROUP 21 INSECTICIDE

GROUP MODE OF ACTION

Mitochondrial complex I electron transport inhibitors

IRAC CHEMICAL SUBGROUPS[1]

METI acaricides and insecticides (21A)

General Group Profile

Members of this group are mainly contact insecticides and miticides. They have no systemic or translaminar activity. Therefore, good coverage of the treated plant is critical to successful management of pest mite population.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(21A) fenazaquin, fenpyroximate, pyridaben, tolfenpyrad

How the Chemistry Works Within the Pest

These mitochondrial electron transport complex I (thus the acronym MET-I) inhibitors act on proteins associated with mitochondrial electron transport complex I (see description of Group 20 Insecticides). Energy production in mitochondria is effectively curtailed when synthesis of ATP is interrupted.

How You Might Observe that Treatments are Working

Once treated, insects and mites briefly survive, becoming less active as their existing energy resources are depleted.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Fenazaquin has contact activity on whiteflies and controls all life stages of spider mites, rust mite and broad mites. Tolfenpyrad is effective against aphids, leafhoppers, caterpillars (early instar), scale insects, thrips, western flower thrips and whiteflies (on ornamental plants in greenhouses). Fenpyroximate provides up to 21 days of control for all mite life stages for spider mites, broad mite, cyclamen mite, eriophyid mites and mealybugs in greenhouse ornamental production. Pyridaben provides up to 45 days of residual control activity against all spider mite and broad mite life stages and also whiteflies in greenhouse and nurseries.

Notes on Interactions with Non-Target Arthropods

Fenazaquin and tolfenpyrad products include a bee advisory box, so label instructions must be followed strictly to prevent impact on honey bees and other pollinators. Tolfenpyrad will harm *Hypoaspis aculiefer* and *Amblyseius swirskii* predatory mites that are commercially available and commonly used to manage western flower thrips. Fenpyroximate is reported to be compatible with predatory mites, but pyridaben is not. METI miticides and insecticides are toxic to fish and aquatic invertebrates. Read product labels carefully and adhere to restrictions on chemigation, buffer zones, drift and runoff, and equipment cleaning procedures.

Origin and History

The METI miticides were discovered in the late 1980s and developed between 1991 and 1993. Fenazaquin was discovered by DowElanco Co., first introduced to the fruit production market in the 1990s, and that introduced by Gowan into the U.S. ornamentals market in 2010. Fenpyroximate was discovered by Nihon Nohyaku Co. and introduced to the ornamental market in the U.S. by SePRO in 2000. Pyridaben was discovered by Nissan Chemical Industries and was introduced to U.S. markets by Gowan in 2002. Initially launched in 2002 for uses in outdoor crop production, tolfenpyrad was introduced to the ornamentals market by SePRO in 2011.

Rotenone is an insecticide that is classified with an IRAC 21B mode of action. This active ingredient was first isolated in the 1890s as an extract from roots of plants in the tropical plant genera *Derris* and *Lonchocarpus* by French botanist and explorer Emmanuel Geoffroy. Rotenone was used as an organic insecticide and miticide option until concerns about its potent toxicity to fish and aquatic species led to its withdrawal from active insecticidal uses in about 2010.

Current Status

Several METI miticides and insecticides are registered in the U.S. Fenazaquin is registered for uses in landscapes, nurseries, greenhouses and interiorscapes; fenpyroximate for nurseries, greenhouses and interiorscapes; pyridaben for nurseries and greenhouses; and tolfenpyrad for greenhouses only.

GROUP 22 INSECTICIDE

GROUP MODE OF ACTION

Voltage-dependent sodium channel blockers

IRAC CHEMICAL SUBGROUPS[1]

Oxadiazines (22A); Semicarbazones (22B)

General Group Profile

Indoxacarb and metaflumizone have both contact and stomach activities, also larvicidal and ovicidal activities. They are designated "reduced-risk" pesticides by EPA and considered replacements for organophosphates.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(22A) indoxacarb; (22B) metaflumizone

How the Chemistry Works Within the Pest

Indoxacarb and metaflumizone block the sodium channels on nerve cells, inhibit the inflow of sodium ions, disrupt the ionic balance, and thus interfere with the normal firing of nerve impulses.

How You Might Observe that Treatments are Working

Once an insect is exposed to the chemicals through direct contact or ingestion of treated plant materials, feeding stops almost immediately, follows by paralysis and death over the next few days.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Indoxacarb is registered for control of European crane fly larvae, grasshoppers, fleas, ants, cockroaches, mole crickets, caterpillars, European pine sawfly larvae, potato leafhopper and sucking insects in urban, household, and agricultural production. Bait-type formulations of indoxacarb are activated when ingested and are often more effective against young caterpillars and mole crickets. Metaflumizone and indoxacarb are currently formulated as ant baits for the management of red imported fire ant and other nuisance ant species.

Interactions with Non-Target Arthropods

Although indoxacarb and metaflumizone are nerve poisons, these compounds have low risk and limited environmental toxicological profiles so the EPA considers them reduced-risk insecticides. Indoxacarb and metaflumizone should not be used in indoor ornamentals production systems where biological control agents are used. These compounds are moderately or highly toxic to predatory mites, predatory bugs, ladybeetles and lacewings. Outdoor applications should be done carefully and adhere to label restrictions on distance to water bodies (15 ft from fresh water bodies or 60 ft from estuarine water bodies) because of potential detrimental impacts to aquatic organisms.

Additional Notes for Optimal Deployment

Indoxacarb is susceptible to hydrolysis in alkaline water, having half-life of only 1 day in water of pH 9. Check the alkalinity of tap or well water and when needed, add a buffering agent to bring alkaline water pH down to 7. Do not apply baits formulated with indoxacarb and metaflumizone when irrigation or rain is expected within the next 24 hours, or to areas that are exceedingly wet or flooded.

Origin and History

The sodium channel blockers were first discovered by research at Phillips-Duphar B. V. in the Netherlands during the early 1970s. However, early development of commercial insecticides failed because of poor photostability, long persistence in soil and high mammalian toxicity. Indoxacarb was developed by DuPont Agricultural Products in the 1990s and first registered and marketed in U.S. in 2000. In late 2012, Syngenta acquired indoxacarb from DuPont. In the late 1990s, metaflumizone was developed by Nihon Noyaku Co. Ltd. and introduced to the U.S. turf and ornamentals industry by BASF in 2013.

Current Status

Indoxacarb and metaflumizone are registered for uses as ant baits on turf, outdoor landscapes, and nurseries. Indoxacarb is also formulated as a sprayable insecticide for control of several caterpillar species, pine sawflies and leafhoppers on ornamental plants in outdoor and interior landscapes, as well as caterpillar and mole cricket species in turf.

GROUP 23 INSECTICIDE

GROUP MODE OF ACTION

Inhibitors of acetyl-CoA carboxylase

IRAC CHEMICAL SUBGROUPS[1]

Tetronic and tetramic acid derivatives

General Group Profile

Spiromesifen has translaminar activity, while spirotetramat is fully systemic (i.e. phloem- and xylem-mobile). As a result, spiromesifen is used as foliar sprays but spirometramat can be used in soil drenches and foliar sprays.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

spiromesifen, spirotetramat

How the Chemistry Works Within the Pest

The enzyme acetyl-CoA plays important roles in normal metabolism and energy production by mitochondria. Acetyl Co-A can also be converted to malonyl-CoA by acetyl-CoA carboxylase, which in turn is used for flavonoid synthesis and elongation of fatty acids yielding protective waxes and cuticle. By targeting acetyl-CoA carboxylase, the Group 23 insecticides shut down lipid, wax and cuticle production. Because waxes and lipid deposits on the surface of insect and mite bodies are crucial to maintaining water balance, their loss causes desiccation of treated insects and mites, leading to their death.

How You Might Observe that Treatments are Working

The affected insects and mites lose water to desiccation and may appear shriveled and dead.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Target pests of spiromesifen include spider mites, tarsonemid mites, tenuipalpid mites, eriophyid mites, and whiteflies. Use of spiromesifen against scale insects is NOT effective. Spirotetramat is effective against adelgids, aphids, leafhoppers, mealybugs, psyllids, rust mites, spider mites, scale insects (crawlers), tarsonemid mites, spittlebugs, thrips (immatures), and whiteflies.

Notes on Interactions with Non-Target Arthropods

Spiromesifen and spirotetramat are compatible with most parasitoid species, lacewings and predatory bugs. However, high toxicity against predatory mites, predatory midges and ladybeetle larvae has been documented.

Additional Notes for Optimal Deployment

Spirotetramat moves slowly in plant vascular tissues and can take up to 2 weeks to yield reductions in pest populations if the insecticide is applied as a drench. Apply drench treatments of spirotetramat in early stages of pest infestation and to small plants, which will allow time for the active ingredient to be translocated to the entire plant.

Origin and History

Spiromesifen, a tetronic acid derivative, was discovered by Bayer Crop Science in the late 1990s as synthetic derivatives of herbicidal protoporphyrinogen oxidase (PPO) chemistry. Spiromesifen products were initially registered in 2005 and are marketed by OHP (for nurseries and greenhouses) and Bayer Environmental Science (for landscapes). Parallel to the development of tetronic acid derivatives, Bayer Crop Science also developed and improved the efficacy of the tetramic acid derivatives. Spirotetramat is a tetramic acid derivative developed by Bayer Crop Science in the late 1990s and introduced to the ornamentals industry by OHP in 2008.

Current Status

Both spiromesifen and spirotetramat are available for pest management on indoor and outdoor ornamental plants.

GROUP 25 INSECTICIDE

GROUP MODE OF ACTION

Mitichondrial complex II electron transport inhibitors

IRAC CHEMICAL SUBGROUPS[1]

Beta-ketonitrile derivatives (25A)

General Group Profile

Cyflumetofen is a contact miticide with activity against multiple spider mite species and all life stages. Mortality of immature and adult spider mites appears within hours of application. Mortality to spider mite eggs occurs within a few days.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

(25A) cyflumetofen

How the Chemistry Works Within the Pest

Similar to other insecticides and miticides that target the electron transport chain in the mitochondria, cyflumetofen also interfere with energy production in the mitochondria. Unlike active ingredients in Group 20, 21 and 24, cyflumetofen inhibits the normal function of the complex II of the electron transport chain. The end result is a failure of mitochondria to produce energy in the form of ATP.

How You Might Observe that Treatments are Working

Mites die when cellular metabolic energy reserves are depleted.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Cyflumetofen is highly effective against spider mites in various indoor and outdoor crop production systems. It does not have activity against eriophyid and tarsonemid mites.

Notes on Interactions with Non-Target Arthropods

Cyflumetofen is compatible with biological control agents including predatory mites, parasitoids, ladybeetles, and predatory bugs commonly used in greenhouse production.

Additional Notes for Optimal Deployment

This is a contact miticide; therefore, thorough coverage of the canopy should be achieved through high volume spray and/or incorporation of a spreader-sticker.

Origin and History

Cyflumetofen was developed by Otsuka AgriTechno Co., Ltd. in Japan in early 2000s. The compound was launched commercially in 2007. BASF introduced cyflumetofen as a miticide to the ornamentals industry in the U.S. in 2014.

Current Status

Cyflumetofen is available for the management of spider mites in greenhouse, nursery, landscape and interiorscapes.

GROUP 28 INSECTICIDE

GROUP MODE OF ACTION

Ryanodine receptor modulators

IRAC CHEMICAL SUBGROUPS[1]

Diamides

General Group Profile

Although the diamides are systemic insecticides, the active ingredient may move slowly within the xylem.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

chlorantraniliprole, cyantraniliprole, cyclaniliprole, tetraniliprole

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How the Chemistry Works Within the Pest

Diamides target normal activities of muscle contractions. When a muscle fiber is contracted, two types of calcium channels are activated: voltage-gated channels that are activated by nerve impulses, and ryanodine receptor channels that are activated by several types of neuronal proteins. When the calcium channels are activated, calcium ions flow into muscle fibers and stimulate contraction. Diamides bind to the ryanodine receptors and cause the calcium channels to remain partially open, which results in excessive and uncontrollable calcium ion release into muscles that disrupts normal muscle function.

How You Might Observe that Treatments are Working

Treated insects twitch or go into muscle spasms & sustained muscular contraction until death.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Target pests of diamides include various chewing and sucking insects. The strength of diamide insecticides rest on their excellent and long-lasting efficacy against certain chewing insects, such as caterpillars and beetle grubs. Efficacy against sucking insects vary greatly among active ingredients. Additional efficacy data are needed before a conclusion could be made about the general efficacy of diamides against sucking insects.

Notes on Interactions with Non-Target Arthropods

Diamides are generally compatible with biological control agents, including predatory mites, parasitoids, ladybeetles, minute pirate bugs and predatory mirid bugs.

Additional Notes for Optimal Deployment

As systemic insecticides, diamides can be applied as foliar spray, bark spray, soil drench, soil injection or broadcast granule. However, diamides are slower in phloem mobility than neonicotinoids. Therefore, it is a good idea to apply diamides upon early pest detection at treatment locations that present persistent episodes of population growth before infestations cause aesthetic or economic injury.

Origin and History

Insecticidal properties of ryanodine, a water-soluble alkaloid produced by the South American plant *Ryania speciosa*, were first discovered in the 1940s by researchers from Rutgers University and Cornell University. The compound was used to control fruit moths, coddling moths, corn earworm, and European corn borer until registration of *Ryania*-containing products was voluntarily cancelled in 1997. DuPont developed chlorantraniliprole, a synthetic ryanodine receptor modulator, that was introduced to markets in 2008. Syngenta acquired the rights to chlorantraniliprole and another synthetic ryanodine analog, cyantraniliprole, in 2012. Cyantraniliprole was introduced in 2014. OHP introduced cyclaniliprole to the ornamental market in 2019. Bayer introduced tetraniliprole to the turf market in 2021.

Current Status

Currently, cyclaniliprole is registered only for ornamental plants, whereas tetraniliprole is registered only for uses in turf. Chlorantraniliprole and cyantraniliprole are registered for both indoor and outdoor uses on turf and ornamental plants.

GROUP 29 INSECTICIDE

GROUP MODE OF ACTION

Chordotonal organ modulators – Undefined target site

IRAC CHEMICAL SUBGROUPS[1]

Pyridine carboxamides

General Group Profile

Flonicamid affects the nervous system associated with insect feeding and movement. Flonicamid has translaminar and systemic activities.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

flonicamid

How the Chemistry Works Within the Pest

Flonicamid was previously classified within IRAC Group 9. It is now understood that, although also affecting chordotonal organs like Group 9 insecticides, flonicamid targets an undefined receptor or enzyme. Following exposure, however, results are similar to Group 9 insecticides. Flonicamid interferes with the neurochemical processes that are controlled by the chordotonal organs. As a result, sensory activity, movement and feeding are inhibited within hours.

How You Might Observe that Treatments are Working

Flonicamid does not provide quick knockdown. Sensory stimuli in insects are impeded, restricting acceleration, balance, gravity perception, and hearing. Treated pests starve to death within about 36-40 hours after application.

General Notes on Target Arthropods

This pest-specific insecticide is only effective against sucking insects, like aphids, whiteflies and mealybugs, and thrips.

Notes on Interactions with Non-Target Arthropods

Flonicamid has low toxicity to predators and parasitoids used in biological control programs, and other non-target organisms.

Origin and History

Discovery and development of flonicamid began in late 1990s by Ishihara Sangyo Kaisha, Ltd. of Osaka, Japan. FMC introduced flonicamid to the ornamental market in the U.S. in 2005.

Current Status

Flonicamid is currently registered for sucking insect and thrips management in greenhouses, nurseries and landscapes.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

GROUP 30 INSECTICIDE

GROUP MODE OF ACTION

GABA-gated chloride channel allosteric modulators

IRAC CHEMICAL SUBGROUPS[1]

Isoxazolines (See note re: update to Current Status on next page.)

General Group Profile

Isocycloseram is a insecticidal compound that affects coleopteran, dipteran, hemipteran, lepidopteran, and thysanopteran pest species. Compounds in this chemical subgroup inhibit nerve signal transmission in invertebrates. Because this chemical disables nerve signaling at a different GABA receptor binding site than cyclodienes [IRAC 2A] and fiproles [IRAC 2B], cross-resistance between MOAs is not known and development of arthropod resistance to this chemistry will be delayed.

Active Ingredients Labeled[2] for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

isocycloseram (Plinazolin technology)[2]

How the Chemistry Works Within the Pest

When isocycloseram is bound to receptors on the GABA-gated chloride channel, chloride ions are prevented from passing through the channel, or "gate". The arthropod nervous system becomes hyperexcited.

How You Might Observe that Treatments are Working

Muscles in the exposed juvenile and adult arthropods contract, immobilizing the affected insect or mite. The affected arthropod is functionally paralyzed and will eventually desiccate or starve to death. Dead arthropods will decompose, releasing nutrients from tissues into the environment.

General Notes on Target Arthropods

Isoclycloseram has broad toxicity to larval and adult species in the coleopteran, dipteran, hemipteran, lepidopteran, thysanopteran insect families.

Notes on Interactions with Non-Target Arthropods

Because of its general toxicity among species in listed orders, isocycloseram will cause death in related species of non-target organisms. Label regulations must be closely followed.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

[2] Plinazolin technology received EPA Registration in December 2025.

Origin and History

Isoxozoline compounds were first synthesized beginning in the early 2000s by Nissan Chemical Industries and recognized for having animal health benefits as antiparastitic, insecticidal or acaricidal activities. By 2019, more than 19 companies had applied for patents on <170 active ingredients in this class of compounds. Subsequent efforts led to development of other compounds in different mode of action classes [e.g., chlorantraniliprole and cyantraniliprole [IRAC Group 28]). A closely related compound to isocycloseram, afoxolaner, developed by Merial, received FDA approval in 2013 as a a commercial parasiticide for flea and tick control in dogs [NexGard]. Isocycloseram was discovered by Syngenta in 2021.

Current Status

Isocycloseram is one of several chemical pesiticides that are classified as IRAC 30 compounds, which have been patented by Syngenta as named pesticide products providing Plinazolin technology. Ornamental (Vykenda) and turf (Atexzo) pesticides received EPA Registration approval in December 2025. Lawsuits filed shortly after are in process (2026), which have challenged EPA approval of isoxolazine compounds that have a single fluorinated carbon, leading to concerns about potential PFAS “forever chemical” status and environmental persistence.

GROUP 31 INSECTICIDE

GROUP MODE OF ACTION

Baculoviruses

IRAC CHEMICAL SUBGROUPS[1]

Granuloviruses, Nucleopolyhedroviruses

General Group Profile

Baculoviruses are a group of viruses that cause deadly diseases in insects and other arthropods. One major characteristic of baculoviruses is their host specificity, i.e. one virus species will only attack one or a small number of related host species. Host specificity makes baculoviruses excellent biological control agents with minimal impact on non-target organisms.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

nucleopolyhedroviruses of *Chrysodeixis includens*, *Helicoverpa armigera*, *Helicoverpa zea*, *Spodoptera exigua* and *Spodoptera frugiperda*

How the Chemistry Works Within the Pest

Baculoviruses are composed of double-stranded DNA protected by a coat of protein called polyhedron. The viral particle, or virion, must be ingested by the host. Within the insect body, the virion released the genetic materials, which take over the host body to produce more viral DNA. The infection causes the eventual death of the host. Baculoviruses typically cause the host to die or modify the behavior of the host to die in a way to maximize release of virions into the environment and contact with the next host.

How You Might Observe that Treatments are Working

The infected insects appear shiny and oily. They are often hanging limply from vegetation. Dead insects decay, then rupture or fall apart, releasing decaying tissues and fluid into the environment.

General Notes on Target Arthropods

Baculoviruses are very host specific. One baculovirus species only infect one or a small number of closely related host species.

Notes on Interactions with Non-Target Arthropods

Baculoviruses have no toxicity to pollinators, biological control agents, and other non-target organisms.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

Origin and History

The study of baculoviruses as biological control agents begun in the 1940s. In recent years, several products have been introduced as biopesticides to assist in the production of agricultural and horticultural crops.

Current Status

Multiple granulovirus and nucleopolyhedrovirus species are available for the management of caterpillar pest species. Currently, nucleopolyhedroviruses for *Chrysodeixis includens*, *Helicoverpa armigera*, *Helicoverpa zea*, *Spodoptera exigua* and *Spodoptera frugiperda* are registered for armyworm, corn earworm, tobacco budworm, cabbage looper and other caterpillars on ornamental plants, and fall armyworm on turf.

GROUP 32 INSECTICIDE

GROUP MODE OF ACTION

Nicotinic acetylcholine receptor allosteric modulators – Site II

IRAC CHEMICAL SUBGROUPS[1]

GS-Omega/Kappa Hxtx-Hv1a peptide

General Group Profile

This is a compound that has similar target site as the other groups that target nicotinic acetylcholine receptors (Group 4 and 5). It is considered a safe and sustainable alternative to other broad-spectrum insecticides.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

GS-omega/kappa Hxtx-Hv1a peptide

How the Chemistry Works Within the Pest

The mode of action of GS-omega/kappa-Hxtx-Hv1a peptide was first thought to be blocking insect calcium and potassium channels. Research in the late 2010s revealed that the peptide has greater affinity to insect nicotinic acetylcholine receptors. Spinosad does not appear to compete with the peptide for the same binding site, although the actual binding site has not been clearly identified.

How You Might Observe that Treatments are Working

The affected insects are paralyzed and eventually die.

General Notes on Target Arthropods

Products containing GS-omega/kappa Hxtx-Hv1a peptide are registered for the management of aphids, spider mites, broad mites, drosophila, psyllids, thrips, and whiteflies. When tank mixed with *Bt* subsp. *tenebrionensis* and *Bt* subsp. *kurstaki*, the product can be used for the control of Colorado potato beetle and caterpillars, respectively. The products are best used against pest population preventively.

Notes on Interactions with Non-Target Arthropods

This chemistry has low toxicity to biological control agents, pollinators, and other non-target organisms.

Origin and History

GS-omega/kappa Hxtx-Hv1a peptide was first identified in the Australian funnel-web spiders in mid-1990s. Vestaron introduced a series of products containing GS-omega/kappa Hxtx-Hv1a peptide to the U.S. green industry in 2016.

Current Status

Currently products are registered for use on greenhouse- and nursery-grown ornamental plants.

GROUP UNB INSECTICIDE

GROUP MODE OF ACTION

Bacterial agents (non-*Bt*) of unknown or uncertain modes of action

General Group Profile

This group includes entomopathogenic bacteria that are not *Bacillus thuringiensis* (which was covered in Group 11). *Burkholderia* sp. is included in IRAC classification, but *Chromobacterium subtsugae* is not. *Chromobacterium subtsugae* is discussed here as an entomopathogenic bacterium.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

Heat-killed *Burkholderia* sp. cells and spent fermentation media; *Chromobacterium subtsugae*

How the Chemistry Works Within the Pest

The mode of action of *Burkholderia* and *C. subtsugae* is not well understood and likely very complex. The bacterium causes disease once the target pest ingests its spores. The bacteria also produce bioactive metabolites or toxins during the stationary growth phase that have insecticidal activity. Inhibition of feeding, reduced egg hatch and reduced fecundity are all associated with infection.

How You Might Observe that Treatments are Working

Infected insects stop feeding soon after infection and die in a few days after feeding inhibition.

General Notes on Target Arthropods

Chromobacterium subtsugae is active against beetles, peach twig borer, caterpillars, aphids, azalea lace bugs, lygus bugs, mealybugs, whiteflies, thrips and mites. A *Burkholderia* sp. product is registered against various caterpillar species, aphids, azalea lacebug, lygus bug, mites, thrips and whiteflies.

Notes on Interactions with Non-Target Arthropods

Compatibility of *Burkholderia* and *Chromobacterium* with biological control agents has not been investigated extensively. No adverse effects on honey bee survival and brood development have been observed.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

Origin and History

Development of bacteria as biopesticides has focused largely on *Bacillus thuringiensis* since its commercialization in the 1920s (see Group 11). Parallel to development of Bt products, *Paenibacillus* (formerly *Bacillus*) *popilliae* was used to manage Japanese beetle grubs, with mixed results. Experimentation continues with other bacterial genera, like *Brevibacillus*, *Chromobacterium*, *Clostridium*, *Paenibacillus*, *Pseudomonas*, *Serratia*, *Xenorhabdus* and *Photorhabdus* (symbionts within entomophathogenic nematodes), and *Yersinia*.

Current Status

Products containing cells and fermentation media of *Burkholderia* sp. and *C. subtsugae* are currently registered for management of various insects and mites on turfgrass and ornamental plants.

GROUP UNE INSECTICIDE

GROUP MODE OF ACTION

Botanical essences (including synthetic, extracts and unrefined oils with unknown or uncertain mode of action)

General Group Profile

This group includes various plant extracts that contain chemically complex sesquiterpenes and other compounds with insecticidal activity. Neem oil products are comprised from clarified hydrophobic extracts. They do not contain azadirachtin, so do not provide insecticidal activity via that mode of action (*see UNK below*).

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

Neem oil

How the Chemistry Works Within the Pest

Spray solution operates on contact with the exoskeleton of soft-bodied arthropods. Chemicals within the extract begin to soften the arthropod cuticle and disrupt cell membrane function or structure. This physical mode of action may result in disruption of insect respiration.

How You Might Observe that Treatments are Working

Outer layers of cuticle on treated insects may appear translucent or "oil soaked". Arthropod activity may be reduced after treatment, with mortality not occurring for hours to several days depending upon contact coverage achieved.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Neem oil is intended for management of juvenile and adult soft-bodied plant feeding mites, aphids, beetles and leafrollers. Insects with waxy coatings (like some mealybug species) may be less susceptible to extract sprays.

Notes on Interactions with Non-Target Arthropods

The product breaks down quickly on treated leaf surfaces. There is almost no residual activity. For this reason, treatments have very little effect on non-target arthropods that are not directly contacted by spray solutions.

Additional Notes for Optimal Deployment

Extract solutions are diluted for pressurized sprayer application to upper and lower leaf surfaces of target crop plants in field and container grown nursery stock plants, annuals, perennials, flowers, shrubs, trees, and non-food greenhouse crop plants. Applications are made to thoroughly wet foliage. Frequent agitation is recommended while spraying. Extract solutions may be most effective against arthropods interacting within the substrate. Reapplication at 7- to 14-day intervals may be required. Not intended for use on fuchsia, hibiscus, roses, impatiens or carnations, for which phytotoxicity has been reported.

Products containing neem oil (or clarified, hydrophobic extract of neem oil) that are obtained *after* azadirachtin is extracted from the neem seed oil, do not contain sufficient azadirachtin to be considered an azadirachtin insecticidal product. Instead, neem oil should be used as plant-derived or horticultural oil. Insecticidal activity of products containing neem oil may result from action of terpenes or other organic compounds that remain in the extracted neem oil solution.

Origin and History

Neem tree products have been used to cure or ameliorate many human ailments. Neem trees are often touted as the "village pharmacy" by subcontinental Indians as far back as 5,000 BC. A German scientist working in Sudan in 1959 observed that neem trees presented the only untouched green vegetation following a desert locust plague. British researchers J. Butterworth and E. Morgan were the first to demonstrate scientifically the antifeedant property of neem extracts (although the active ingredient was not identified at the time) on desert locusts in 1968. It was not until 1985, following the simultaneous report of the complete structure of azadirachtin by three different research groups. Currently, azadirachtin used for pest control is extracted mainly from neem seed kernels. A synthesis process has been developed by Professor Steven Ley of University of Cambridge and colleagues in 2007, which may increase the supply of azadirachtin.

Current Status

Insects that are repeatedly exposed to azadirachtin can become habituated and the antifeeding response can slowly become reduced. Insects can also overcome the antifeeding effect if azadirachtin is applied to their most preferred food plants. If habituation occurs, another non-azadirachtin product can be applied to extend the product efficacy.

GROUP UNF INSECTICIDE

GROUP MODE OF ACTION

(Entomopathogenic) fungal agents of unknown or uncertain mode of action

General Group Profile

There are several characteristics that make entomopathogenic fungi (EPF) particularly attractive for developers and users of microbial control products:

- More than 700 fungal species and strains from 90 genera are known to be pathogens of insects and mites. Each insect or mite species is afflicted by at least one fungus species or strain and each fungus could potentially be developed into a product. Experiments have been conducted on many species from the genera *Aschersonia*, *Agerata*, *Beauveria*, *Verticillium*, *Sphaerostilbe*, *Podonectria*, *Myriangium*, *Cordyceps* (formerly *Isaria, Hirsutella,* and *Paecilomyces*), and *Metarhizium.*
- Products containing EPF are usually formulated using dormant spores of the fungi and can be applied as foliar spray or soil drench using the same equipment as used for the other insecticides. Because of how these EPF products are applied, they are sometimes called biopesticides.
- The use of dormant spores as the main life stage for delivery also allows the fungi to survive for an extended time under adverse environmental conditions (e.g., sun and heat) following application.
- Most EPF products can be produced using a fermentation process and at a relatively low cost.
- Some species or strains of fungi have a broad host spectrum; both sap sucking and chewing insects are susceptible to these broad-spectrum species or strains.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

Beauveria bassiana, Cordyceps (formerly *Isaria* & *Paecilomyces*) *formosorosea,*

Metarhizium anisopliae

How the Chemistry Works Within the Pest

Soon after a fungal spore in the spray solution lands on an insect's exoskeleton, the spore germinates and produces a hyphal tube that penetrates the cuticle. Penetration is aided by secreted enzymes that can dissolve the proteins, lipids, chitin and other components of the arthropod cuticle. Once the fungus penetrates into the hemocoel (i.e. the body cavity of arthropods), hyphae change in growth morphology into a yeast-like phase that circulates throughout the insect hemolymph. The fungus also produces toxins and secondary metabolites that kill the insect host. The fungus then reverts to the hyphal stage, which then produces spores that will result in infection of additional hosts.

How You Might Observe that Treatments are Working

Cadavers of infected insects often appear off-colored and powdery. When humidity is high, mycelium may grow from the cadaver. *Beauveria* and *Isaria* mycelia is whitish, and green for *Metarhizium*.

General Notes on Target Arthropods

EPFs are generally broad-spectrum, with high effectiveness when used against soft-bodied insects.

Notes on Interactions with Non-Target Arthropods

EPFs are considered compatible to biological control agents and pollinators.

Additional Notes for Optimal Deployment

EPF can be applied as foliar sprays or soil drenches, depending upon the habitat occupied by the targeted pest. Regardless of the product used, avoid tank mixing with fungicides and prolonged storage in very high or low temperature. EPF solutions should be used within 24 hours after mixing. Because the fungal spores will only germinate when in contact with insect cuticle, it is important to achieve complete coverage of the plant and soil during application. Temperature and humidity are crucial to the germination of the fungal spores. Most products work best between 60 and 80 F and for at least 10-12 hours with relative humidity above 85%. EPF products are considered to have high levels of safety to crops but it is always a good idea to test for potential phytotoxicity on a small number of plants before spraying the entire crop.

Origin and History

Beauveria bassiana occurs naturally in soils and is distributed worldwide. This fungus species is also called white muscadine disease, named after the white sporulating structures that emerge from infected insects. This disease is named after the Italian entomologist Agostino Bassi, who in 1835 discovered this fungus species killing silkworm caterpillars being reared for the silk industry. Many strains of the fungus have been developed into commercial products. This fungus species has a wide host range, attacking mites and insects across nearly all orders. *Beauveria bassiana* is particularly effective against nymphs of sucking insects and larvae of beetles active on leaf surfaces and in the soil.

Metarhizium anisopliae is also a common soil fungal entomopathogen; it is commonly referred to as the green muscadine disease. Spores produced by *M. anisopliae* are at first white but soon turn green. More than 200 insect species are colonized by *M. anisopliae* and some strains are host specific. The generalist strain is typically used in the formulation of commercial products.

Cordyceps fumosorosea (formerly known as *Isaria fumosorosea* and *Paecilomyces fumosoroseus*) is more closely associated with its insect host than either *B. bassiana* or *M. anisopliae*. *Cordyceps fumosorosea* is less commonly found in the soil. This fungus infects species in more than 25 insect families, as well as many species of mites

Current Status

Despite the many advantages and growing interest, EPF products remain a relatively small percentage of total insecticidal active ingredients used in turf and ornamental markets. In part, the small market share by EPF products may be related to longer times needed to reduce pest populations, with disease often developing 3-7 days after application. According to a survey by Faria and Wraight (2007, Biological Control 43: 237-256), 33.9% of microbial insecticides or miticides of the world contain *B. bassiana*, 33.9% contain *Metarhizium anisopliae*, 5.8% contain *Cordyceps* (formerly *Isaria*) *fumosorosea*, 4.1% contain *Beauveria brongniartii*, 1.8% contain *Hirsutella thompsonii*, and 1.2% contain *Lecanicillium lecanii* (= *Verticillium lecanii*). In the U.S., only products containing *B. bassiana*, *C. fumosorosea* and *M. anisopliae* are available, but commercial products containing viable *M. anisopliae* have not been accessible since 2019.

GROUP*	UNM	INSECTICIDE

** These are insecticides and miticides that are not classified by IRAC, thus do not fit within a well-designated group.*

Group Type

Horticultural, petroleum or paraffinic oils

General Group Profile

Horticultural oils are a group of lightweight oils that are used for pest management. They are applied as diluted spray onto the plant surface or the target pests' bodies.
Horticultural oils are versatile and can be used in all situations. They are effective against many soft-bodied insects, have a short re-entry interval (REI) of 4 hours, and present very low risks to the environment, human, non-target organisms, and beneficial insects.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

mineral oil, paraffinic oil, refined petroleum distillate, vegetable oil

There are different sources of horticultural oils that are used as pesticides. An emulsifier is often added to most oil-based products to enable easy mixing with water or other pesticide solutions.

1) Petroleum or mineral oils: Summer/horticultural oil and dormant oil, with which we are most familiar, are refined petroleum products. Summer/horticultural oils are widely available and come in many different blends and trade names. Dormant oils are heavier and less refined petroleum oils that are effective against scale insects, aphids and mites on dormant plants and should be used after winter hardening and before bud break (uses following bud break may result in damage to bid or emerging leaves). Summer/horticultural oils can be used safely on foliage and flowers. Impurities, such as sulfur and other organic compounds, have been removed from the mineral oils and thus reduced the potential for phytotoxicity. These products are typically used at 1 or 2% dilution.
2) Vegetable oils: Some products are formulated with refined or emulsified vegetable oil, such as cottonseed oil and soybean oil. Vegetable oils are often used as adjuvants with added pesticidal activity.

Some plant-derived essential oils, including citrus oil, peppermint oil and cedarwood oil, are being promoted as organic pesticides. Due to reports of phytotoxicity across various use rates, some essential oils appear to work better as herbicides than insecticides. Research is needed to increase the quality, efficacy and safety of these products.

How the Chemistry Works Within the Pest

Horticultural oils kill in several ways: 1) block the spiracles (air holes) of the insects, causing death by asphyxiation; 2) disrupt the integrity of insect and mite cuticle and cell membranes; 3) interfere with normal metabolism by interacting with fatty acids; and 4) disrupt normal feeding behaviors of aphids.

How You Might Observe that Treatments are Working

Contacted insects die quickly.

General Notes on Target Arthropods

Horticultural oils are effective against soft-bodied insects, particularly aphids, whiteflies, scale insects, adelgids, leafhoppers, spider mites and eriophyid mites.

Interactions with Non-Target Arthropods

Direct application and contact of horticultural oil can be detrimental to small, soft-bodied biological control agents (e.g., predatory mites). Avoid using horticultural oils when beneficial or desirable predatory insects are active. Once spray solutions have dried, horticultural oils provide no residual activity, and are then considered compatible with biological control agents and pollinators.

Additional Notes for Optimal Deployment

Consequent to short residual activity, re-application is typically needed within one or two weeks, particularly to control active or fast-reproducing pest arthropods. Because horticultural oil solutions only work when contacted by the pest, complete canopy coverage is essential. This is particularly true for managing scale insects or spider mite eggs. Mixing with horticultural oil can enhance the efficacy of some insecticides and miticides. Under certain environmental conditions even the most refined mineral oil can cause damage to the plants. Horticultural oils can generally be used safely if temperatures do not exceed 90 F or fall below freezing. Also avoid using horticultural oils when rain is expected, when plant tissues are wet, or when humidity exceeds 90%. High moisture and humidity levels will delay the evaporation of oil solution and can cause plant damage. Certain plant species, particularly conifers, redbuds and some maples, can be sensitive to horticultural oil sprays. Responses of other plant species may depend on the stress level of the plants. Crops suffering from drought-stress are more likely to be damaged.

Origin and History

In the 18th century kerosene was used to treat insect infestations on crops. Although the kerosene application was quite effective, it also had high phytotoxicity to the plants that it was supposed to protect. In the mid-1900s, with improvements in refining technology, a new generation of petroleum-based oils or mineral oils was produced as pesticides. These petroleum oils were lightweight, contained fewer impurities, and lower in phytotoxicity when used as directed.

Current Status

Many horticultural oil products are commercially available.

GROUP* *UNK* INSECTICIDE

** These are insecticides and miticides that have modes of action that are unknown or unclear, thus are not currently classified by IRAC and do not fit within a clearly delineated group.*

GROUP MODE OF ACTION

Unknown

IRAC CHEMICAL SUBGROUPS[1]

Azadirachtin

General Group Profile

Azadirachtin and its analogues are botanical terpenoids extracted mainly from seed kernels, but also in smaller amounts from fruits, seeds, twigs, stem and bark of the neem tree (*Azadirachta indica*), which is a tropical evergreen native to arid regions of the Indian Subcontinent. Azadirachtin has systemic activity, is non-volatile, and is effective by contact or ingestion. Some product labels allow for soil drench, soil injection, trunk injection or chemigation. Antifeeding effects are expressed following ingestion by insects. When used as a systemic insecticide, azadirachtin is more effective against insects feeding on the foliage than other plant parts.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

azadirachtin

How the Chemistry Works Within the Pest

Azadirachtin displays both antifeeding and growth disrupting properties against more than 200 insect species. However, the actual mode of action is unclear and IRAC has not classified azadirachtin as either an antifeedant or an insect growth regulator. Once ingested, azadirachtin appears to turn on deterrent neuron(s) in susceptible insects that causes them to stop feeding on treated plants. Both ingestion and contact with azadirachtin induces growth or molting disruption in larvae and reproductive failure in adults. Larval growth inhibition is most likely caused by interference of juvenile hormone or other growth hormones. Such growth inhibitory responses become stronger as treatment dosage increases. Even if the larvae survive a low dose of azadirachtin, fecundity may be subsequently reduced. Reproductive failure has also been reported for adult arthropods.

How You Might Observe that Treatments are Working

Larvae treated with azadirachtin often exhibit growth inhibition and malformation of body parts, which eventually leads to death. Adults, by contrast, suffer from weight loss and fail to produce mature eggs. Eggs treated with azadirachtin often fail to hatch.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Azadirachtin products are registered for the control of various species of adelgids, aphids, armored scales, grasshoppers, leaf feeding beetles and weevils, borers, caterpillars, flies, grubs, lacebugs, leafhoppers, leafminers, mealybugs, mites, mole crickets, psyllids, sawflies, soft scales, thrips, and whiteflies. Some products include plant parasitic nematodes as target pests.

Notes on Interactions with Non-Target Arthropods

Azadirachtin is readily degraded in the environment, leading to short residual longevity, and is nontoxic to mammals. In turn, this compound is a good alternative for natural or organic pest management. Most azadirachtin products are approved for organic production. Azadirachtin products are generally compatible with biological control agents. However, direct contact with insecticide solutions following topical applications can be detrimental to the survival of adult parasitoids and predatory bugs.

Additional Notes for Optimal Deployment

Products containing neem oil (or clarified, hydrophobic extract of neem oil) that are obtained *after* azadirachtin is extracted from the neem seed oil, do not contain sufficient azadirachtin to be considered an azadirachtin insecticidal product. Instead, neem oil should be used as a plant-derived or horticultural oil. Insects that are repeatedly exposed to azadirachtin can become habituated and the antifeeding response can slowly be reduced. Insects can also overcome the antifeeding effect if azadirachtin is applied to their most preferred food plants. If habituation occurs, another non-azadirachtin product can be applied to extend the product efficacy.

Origin and History

Neem tree products have been used to ameliorate many human ailments. Neem trees are often touted as the "village pharmacy" in South Asia as far back as 5,000 B.C. A German scientist working in Sudan in 1959 observed that neem trees presented the only untouched green vegetation following a desert locust plague. British researchers J. Butterworth and E. Morgan were the first to demonstrate scientifically the antifeedant property of neem extracts (although the active ingredient was not identified at the time) on desert locusts in 1968. It was not until 1985 when the complete structure of azadirachtin was reported simultaneously by three different research groups. Currently, azadirachtin is extracted mainly from neem seed kernels. A synthesis process has been developed by Professor Steven Ley of University of Cambridge and colleagues in 2007, which may increase the supply of azadirachtin.

Current Status

A large number of azadirachtin products are available for use in the green industry.

GROUP* *UNK* INSECTICIDE

** These are insecticides and miticides that have modes of action that are unknown or unclear, thus are not currently classified by IRAC and do not fit within a clearly delineated group.*

GROUP MODE OF ACTION

Unknown

IRAC CHEMICAL SUBGROUPS[1]

Dicofol

General Group Profile

Dicofol has historically been considered an organochlorine compound. It is classified as a bridged diphenyl acaricide. Dicofol was very similar to DDT, which is an intermediate compound formed in the steps to production of dicofol. Regardless, the mode of action of dicofol was never conclusively established. Dicofol has high mammalian toxicity and long persistence in the soil; therefore, its registration has been withdrawn from use in the U.S. This information is retained to document a product that may be remembered by growers and landscape managers.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

*dicofol**

How the Chemistry Works Within the Pest

Despite its long history and use, the precise mode of action of dicofol remains unclear. Dicofol is suspected to inhibit enzyme activity and cause hyperactivity in the central nervous system.

How You Might Observe that Treatments are Working

Mites exposed to dicofol die very quickly.

General Notes on Target Arthropods

Dicofol was used as a general miticide in the ornamental industry.

Interactions with Non-Target Arthropods

Dicofol was considered incompatible with most biological control agents. Its use is strongly discouraged in any plant production and maintenance system where biological control is being practiced.

Origin and History

Dicofol is an old miticide, first marketed in the U.S. by Rohm and Haas in the 1950s.

Current Status

EPA has canceled the registration of Kelthane. Existing stocks of any end-user products was allowed until 31 October 2016, after which all products were to be properly disposed.

[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

GROUP* *UNK* INSECTICIDE

** These are insecticides and miticides that have modes of action that are unknown or unclear, thus are not currently classified by IRAC and do not fit within a clearly delineated group.*

GROUP MODE OF ACTION

Unknown

IRAC CHEMICAL SUBGROUPS[1]

Pyridalyl

General Group Profile

Pyridalyl is primarily effective via contact and by ingestion. Although some translaminar activity may occur, it is still important to achieve thorough coverage of the entire plant (through foliar spray or ultra-low volume fogging) for the best efficacy.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

pyridalyl

How the Chemistry Works Within the Pest

The mode of action of pyridalyl is currently unknown. Two potential modes of insecticidal activity have been proposed. Pyridalyl may selectively inhibit cellular protein synthesis. Alternatively, the metabolism of pyridalyl by cytochrome P450 may include formation of reactive oxygen species (also called free oxygen radicals) that, then cause oxidative damage to cellular molecules and subsequent cell death.

How You Might Observe that Treatments are Working

Treated pests die within 3 days.

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[1] http://www.irac-online.org/modes-of-action/. Mention of trade names does not imply approval, endorsement, or guarantee of the products.

General Notes on Target Arthropods

Pyridalyl targets thrips and caterpillars on greenhouse-grown ornamentals and non-bearing fruit and nut trees and vines.

Interactions with Non-Target Arthropods

Pyridalyl is compatible with predatory mites (*Amblyseius*, *Neosieulus*, *Phytoseiulus* and *Hypoaspis* spp.), ladybeetles, lacewings, parasitoids and minute pirate bugs, making this a valuable tool in developing an IPM program.

Additional Notes for Optimal Deployment

In situations where the resident thrips population is large, or when there is considerable migration of thrips into the greenhouse, reapplication with pyridalyl is recommended after between 14 and 21 days. No phytotoxicity from pyridalyl has been observed on impatiens, begonia, chrysanthemum, fuschia, geranium, marigold, New Guinea impatiens, pansy, petunia, Gerbera daisy, verbena, and zinnia.

Origin and History

Dichloroallyl alcohol derivatives, which are the progenitor compounds to pyridalyl, have been reported since the 1980s to have insecticidal activity. Pyridalyl was first described in 2002 and developed by Sumimoto Chemical Co., Ltd. in Japan with the intent of discovering a new insecticide against caterpillar pests of cotton, vegetables and fruits that had developed resistance to existing insecticides. Valent USA Corporation introduced the first product containing pyridalyl to U.S. markets in 2008.

Current Status

Currently, pyridaryl is registered for use in commercial greenhouse only. No product is labeled for outdoor or residential uses.

GROUP* *unclassified* INSECTICIDE

** These are insecticides and miticides that are not classified by IRAC, thus do not fit within a well-designated group.*

Group Type

Entomopathogenic nematodes (EN)

General Group Profile

Entomopathogenic nematodes (EN) are parasitic roundworms of insects. EN are soft-bodied and unsegmented and occur naturally in the soil. In the laboratory, ENs can attack a wide range of insects. Host range in the field is narrower, depending on environmental conditions and ecological or behavioral barriers (such as the absence of susceptible arthropod hosts).

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

Most commercially-available ENs belong to two nematode families:

Heterorhabditidae (*Heterorhabditis bacteriophora*, *H. megidis*, *H. indica* and *H. marelatus*), and;
Steinernematidae (*Steinernema glaseri*, *S. kraussei*, *S. carpocapsae*, *S. feltiae*, *S. riobrave,* and *S. scapterisci*)

How the Chemistry Works Within the Pest

The infective juvenile (or dauer) stage is the EN life stage responsible for attacking insects. ENs can be ambushers (i.e. those that lie-in-wait to attack any mobile insects that pass by), cruisers (i.e. those that active search for less mobile insects using volatiles and vibrations emitting from the insects), or can present a combination of both strategies. Infective juvenile nematodes enter an insect's body through direct openings (spiracles, mouth or anus) or intersegmental membranes on the cuticle. Once inside, ENs move into the hemocoel and release the symbiotic bacteria that are housed inside the ENs' bodies. The bacteria multiply and kill the infected insect. The ENs then feed on the insect tissues killed by the bacteria and continue their development into adulthood. Adult ENs reproduce and produce more infective juveniles, which are released into the environment.

How You Might Observe that Treatments are Working

ENs and their symbiotic bacteria often kill the infected insects very quickly. Insects killed by heterorhabditid nematodes turn red, whereas those killed by steinernematid nematodes turn brown or tan.

General Notes on Target Arthropods

Most commercially available EN species are host specific. *Steinernema kraussei* is registered for the management of black vine weevil larvae; *S. feltiae* for larvae of fungus gnats and shoreflies, and western flower thrips; *H. megidis* for weevils; and *H. indica* for fungus gnats and root mealybugs.

Interactions with Non-Target Arthropods

ENs are compatible with biological control agents commonly used against insect and mite pests of ornamental plants. Those biological agents released in the canopy are not in contact with the ENs applied to the soil substrate, or medium and are therefore not impacted. The fast movement of soil-applied biological control agents also denies opportunity of infection by ENs. ENs are generally compatible with most pesticides used in pest management program. Users are advised to consult with the EN suppliers to determine the compatibility of ENs and other pesticides or fertilizer.

Additional Notes for Optimal Deployment

All products containing EN are formulated with fully active or semi-dormant infective juveniles. Therefore, different from other microbial or fungal products that are formulated with the dormant stage, products containing EN should be purchased just before the application, and stored properly and according to manufacturer instructions for no longer than 3 months or exceeding the time limit indicated by the manufacturer. A small sample of spray solution should be examined with microscopes or handlens before application to verify the viability of the ENs (healthy juvenile stages will move around in the solution). Most ENs are host-specific; therefore, each EN product should be used against its intended pests. ENs are very sensitive to temperature and moisture level. Application should be made at temperatures most suitable for the ENs and the treated areas should be kept wet for at least 8 hours and protected from direct exposure to sunlight. ENs can be applied with most application equipment or sprayers. Filters in the sprayers should be removed and high pressure (greater than 300 psi) should be avoided. Large diameter nozzles and high volume (greater than 100 gallons per acre) are recommended. Check manufacturers' recommendations if ENs are to be tank mixed with other pesticides and fertilizer.

Origin and History

Steinernema glaseri was the first nematode to be utilized for pest management (against Japanese beetle grubs in the 1930s). In the 1970s and 1980s, uses of *S. carpocapsae* achieved excellent control of soil-dwelling insects, but efficacy of these ENs against foliage-feeding insects in the 1950s to 1980s failed and clearly demonstrated their weakness in adapting to foliage environment. Recent development of ENs for pest management has focused on soil-dwelling insect larvae.

Current Status

Several *Heterorhabditis* and *Steinernema* species are produced by the major biological control agent suppliers for management of various immature soil-dwelling, boring or concealed insect pests.

GROUP* *unclassified* INSECTICIDE

** These are insecticides and miticides that are not classified by IRAC, thus do not fit within a well-designated group.*

Chemical Class Type

Potassium salts of fatty acids (a.k.a. insecticidal soap)

General Group Profile

Contact insecticide with limited to no residual activity.

Active Ingredients Labeled for Commercial Nursery, Greenhouse, Professional Landscape or Turfgrass Management Uses

Potassium salts of fatty acids

How the Chemistry Works Within the Pest

The mode of action of insecticidal soaps is not fully understood. There are generally four hypotheses. First, insecticidal soaps may penetrate cuticle of insects and disrupt cell integrity, leading to cell leakage, cell collapse and eventually death. Insecticidal soaps also may cause death by blocking the spiracles (or breathing holes) of the insects and causing asphyxiation. Thirdly, by penetrating the cells, insecticidal soaps may act as an insect growth regulator by disrupting the normal functions of growth hormones and metamorphosis. And lastly, insecticidal soap molecules may penetrate deep into the mitochondria, disrupt the process of oxidative phosphorylation, and inhibit the normal process of energy production.

How You Might Observe that Treatments are Working

Contacted insects desiccate and die.

General Notes on Target Arthropods

Insecticidal soaps are inexpensive and effective against a large group of soft-bodied insects, including aphids, whiteflies, mealybugs, scale crawlers, thrips, twospotted spider mites, and leafhoppers. For insecticidal soap solutions to be effective, target insects must be completely wetted by spray coverage. Efficacy is generally lower when insecticidal soaps are used to control older instars and larger, harder-bodied insects. Frequent reapplications may be needed, particularly if target pests are highly mobile or reintroduced to growing areas.

Notes on Interactions with Non-Target Arthropods

Insecticidal soap residues on plant surfaces degrade quickly and are almost non-toxic to organisms that encounter the residue once the spray solution has dried. Insecticidal soaps are generally considered safe to bees and natural enemies or compatible with biological control organisms. It is still prudent to avoid spraying directly on bees, ladybeetles, predatory mites and other natural enemies.

Additional Notes for Optimal Deployment

An additional benefit of insecticidal soaps is that they have greater efficacy at higher temperatures (+90 F) and relative humidity (85 percent). This characteristic makes insecticidal soaps a good alternative to horticultural oils, which are not recommended for use when temperatures are above 90 F. Some plant species are sensitive to phytotoxicity caused by insecticidal soaps, presenting leaf curling, distortion, discoloration, leaf drop, die-back, and other conditions. Sensitive plant species include bleeding heart, crown of thorns, Easter lily, gardenia, hawthorn, horse chestnut, Japanese maple, lantana, maidenhair fern, mountain ash, nasturtium, *Prunus* (cherries, plum), portulaca, sweet pea, and some tomato cultivars. Azalea, begonia, fuchsia, geranium and impatiens are moderately sensitive. The severity of phytotoxic responses in plants may vary among species and cultivars and is condition dependent. Phytotoxicity, particularly for conifers, appears to be more severe during a drought or if the plants are under drought stress. Herbaceous plant species or soft vegetative tissues are more susceptible to phytotoxicity than woody species or tissues. Larger and older plants are more tolerant than young, succulent plants. Insecticidal soap solution of a higher rate also has a higher potential for causing phytotoxicity. Test for phytotoxicity to insecticidal soaps by spraying on a few plants of each species and observing for at least 24 hours to determine if any phytotoxic reactions occur before applying the same solution to the entire crop or planting.

Origin and History

Like the use of kerosene, the use of soaps for pest management began as early as the 18th century. Because of a high content of impurities and the caustic nature of the remaining alkali, however, a high level of phytotoxicity was often observed. The first safe insecticidal soap was registered for use in 1947.

Current Status

Many insecticidal soap products are commercially available for uses on ornamental plants.

Appendix A.
An IRAC Organization Table for Insecticide and Miticide Products[1,2]

Table 1. Products that are (*or have been*) Labeled for Ornamental Plant Use Sites. A partial listing of insecticide and miticide products organized by the Insecticide Resistance Action Committee (IRAC) numerical code for each classified Mode of Action, followed by the chemical subgroup (in bold), if any. Beneath the chemical subgroups are listed the pesticidal active ingredients that are or have been labeled for ornamental plant-associated use sites. Beside these are names or a partial listing of selected product representatives. *Note: product names indicated with a superscript pound sign ([#]) are informational for the IRAC group; label examples do not include an ornamental plant-associated use site.*

IRAC 1: Acetylcholinesterase inhibitors

(1A) Carbamates

carbaryl	6.3% Carbaryl Granular, Carbaryl 4L

(1B) Organophosphates

acephate	Acephate, Orthene, 1300 Orthene TR
chlorpyrifos	Dursban 50W
diazinon[2]	Diazinon
dicrotophos	Inject-A-Cide B
dimethoate	Dimethoate 4EC, Dimethoate 400EC
malathion	Malathion 5, Malathion 8F
*methidathion**	*Supracide 2E*
*oxydemeton methyl**	*Harpoon*[2], *MSR Spray Concentrate*[2]
trichlorfon	Dylox 420 SL

IRAC 2: Gamma-aminobutyric acid (GABA)-gated chloride channel antagonists

(2A) Cyclodiene organochlorines[2]

*endosulfan**

(2B) Phenylpyrazoles and **Fiproles**

fipronil	TopChoice

IRAC 3: Sodium channel modulators

(3A) Pyrethroids

bifenthrin	Ascertain TR, OnyxPro, Talstar S Select, Talstar Nursery G
cyfluthrin	Decathlon 20 WP
beta-cyfluthrin	Tempo Ultra WP, Tempo SC Ultra
gamma-cyfluthrin	Scion
lambda-cyhalothrin	Scimitar CS, Scimitar GC
cypermethrin	Demon WP
alpha-cypermethrin	Fendona
deltamethrin	DeltaGard G
fenpropathrin	Tame 2.4 EC
tau-fluvalinate	Mavrik Aquaflow
permethrin	Astro, Perm-Up 3.2 EC, Permethrin Pro
pyrethrins	Tersus, Pyganic, Pyreth-It
pyrethrum	Pyrethrum TR

(3A + 4A) Pyrethroids + Neonicotinoids

bifenthrin + clothianidin	Aloft LC G, LC SC
bifenthrin + imidacloprid	Allectus *(plus fertilizer)*
cyfluthrin + imidacloprid	Discus N/G
lambda-cyhalothrin + thiamethoxam	Tandem
zeta-cypermethrin & bifenthrin + imidacloprid	Triple Crown T&O

IRAC 4: Nicotinic acetylcholine receptor competitive modulators

(4A) Neonicotinoids

acetamiprid	TriStar 8.5 SL
clothianidin	Arena 50 WDG
dinotefuran	Safari 20 SG, Transtect 70 WSP, Zylam Liquid
imidacloprid	CoreTect, Discus Tablets, Imidashot DF, Marathon II, Marathon 60WP, Merit, Midash 2SC, Xytect 75WSP; Xytect 2F
thiamethoxam	Flagship 25WG, Meridian 25WG

(4B) Nicotine *(a botanical extract)**

(4C + 5) Sulfoxaflor + Spinosyns

sulfoxaflor + spinetoram	XXpire

(4D) Butenolides

flupyradifurone	Altus

IRAC 5: Nicotinic acetylcholine receptor allosteric modulators

Spinosyns

spinosad	Conserve SC, Entrust

IRAC 6: Glutamate-gated chloride channel allosteric modulators

Avermectin and milbemycin glycosides

abamectin	Lucid, Avid, Aracinate TM, Award II
emamectin benzoate	Arbormectin, Tree-äge
*milbemycin**	*Ultiflora**[2]

(6 + 20D) Avermectin + Bifenazate

abamectin + bifenazate	Sirocco

IRAC 7: Juvenile hormone mimics

(7A) Juvenile hormone analogues

s-kinoprene	Enstar AQ
s-methoprene	Extinguish Plus, Extinguish Professional

(7B) **Juvenile hormone analogues**

*Fenoxycarb**	*Award**[2], *Preclude TR**[2]

IRAC 7: Juvenile hormone mimics *(continued)*

(7C) Pyridine insect growth regulators

pyriproxifen	Distance IGR, Distance Fire Ant Bait, Fulcrum

IRAC 8: Miscellaneous non-specific (multi-site) inhibitors

(8C) Cryolite

cryolite (sodium aluminofluoride)	Kryocide

(8D) Borates

sodium tetraborohydrate decahydrate	Prev-AM Ultra

IRAC 9: Chordotonal organ transient receptor potential vanilloid (TRPV) channel modulators

(9B) Pyridine azomethine derivatives

pymetrozine	Endeavor
pyrifluquinazon	Rycar

(9D) Pyropenes

afidopyropen	Ventigra

IRAC 10: Mite growth inhibitors affecting CHS1

(10A) Mite growth inhibitors

clofentezine	Notavo
hexythiazox	Hexygon DF

(10B) Etoxazole

etoxazole	Beethoven TR, TetraSan 5 WDG

IRAC 11: Microbial disruptors of insect midgut membranes

***Bacillus thuringiensis* (*Bt*) & insecticidal proteins**

Bt subsp. *aizawai*	XenTari
Bt subsp. *galleriae*	GrubGONE! G
Bt subsp. *israelensis*	Gnatrol WDG
Bt subsp. *kurstaki*	Dipel Pro DF
Bt subsp. *tenebrionensis*	Novodor

IRAC 12: Inhibitors of mitochondrial ATP synthase

(12B) Organotin miticides

fenbutatin-oxide	Vendex

IRAC 13: Uncouplers of oxidative phosphorylation via disruption of the proton gradient

Pyrroles

chlorfenapyr	Pylon

IRAC 15: Inhibitors of chitin biosynthesis affecting CHS1

Benzoylureas

diflubenzuron	Adept, Dimilin, Durant 2L IGR (turf)
novaluron	Pedestal

IRAC 16: Inhibitors of chitin biosynthesis, type 1

Buprofezin

buprofezin	Talus 70DF

IRAC 17: Moulting disruptor, Dipteran

Cyromazine

cyromazine	Citation

IRAC 18: Ecdysone receptor agonists

Diacylhydrazines

methoxyfenozide	Intrepid 2F
tebufenozide	Mimic 2LV

IRAC 20: Mitochondrial complex III electron transport inhibitors

(20A) Hydramethylnon

hydramethylnon	Amdro Pro

(20B) Acequinocyl

acequinocyl	Shuttle-O

(20D) Bifenazate

bifenazate	Banter 4SC, Floramite SC

IRAC 21: Mitochondrial complex I electron transport inhibitors

(21A) METI acaricides and insecticides

fenazaquin	Magus, Magister SC
fenpyroximate	Akari 5SC
pyridaben	Sanmite
tolfenpyrad	Hachi-Hachi SC

IRAC 22: Voltage-dependent sodium channel blockers

(22A) Indoxacarb

indoxacarb	Advion, Provaunt

(22B) Metaflumizone

metaflumizone	Siesta

IRAC 23: Inhibitors of acetyl CoA carboxylase

Tetronic and tetramic acid derivatives

spiromesifen	Forbid 4F, Savate
spirotetramat	Kontos

IRAC 25: Mitochondrial complex II electron transport inhibitors

(25A) Beta-ketonitrile derivatives

cyflumetofen	Sultan

IRAC 28: Ryanodine receptor modulators

Diamides

chlorantraniliprole	Acelepryn
cyantraniliprole	Mainspring, Ference (turf)
cyclaniliprole	Sarisa
tetraniliprole	Tetrino (turf)

(28 + 29) Diamides + Flonicamid

cyclaniliprole + flonicamid	Pradia

IRAC 29: Chorodontal organ modulators – undefined target site

Pyridine carboxamides

flonicamid	Aria

IRAC 30: GABA-gated chloride channel allosteric modulators

Isoxazolines

Isocycloseram (Plinazolin technology)	Vykanda, Atexzo (turf)

IRAC 31: Baculoviruses

Granuloviruses (GVs), Nucleopolyhedroviruses (NPVs)

NPVs	lepidopteran spp. (Gypcheck#, Heligen#, Lepigen#)

IRAC 32: Nicotinic acetylcholine receptor allosteric modulators, Site II

GS-Omega/Kappa Hxtx-Hv1a peptide

GS-Omega/Kappa Hxtx-Hv1a peptide	Spear-T, Spear Lep

UNB: Bacterial agents (non *Bt*) of unknown or uncertain modes of action

Entomopathogenic bacteria

*Burkholderia**	Venerate XC
(*heat-killed cells and spent fermentation media)	
Chromobacterium subtsugae	Grandevo WDG

UNE: Botanical Essences (& synthetic extracts)

Neem oil

Neem oil	Trilogy, Triact 70
Botanical oil	Captiva Prime, Tetracurb, Proud, etc.

UNF: (Entomopathogenic) Fungal agents of unknown or uncertain modes of action

Entomopathogenic fungi

Beauveria bassiana	BioCeres WP, BotaniGard ES & 22 WP, Mycotrol O, Naturalis-L
Coryceps formosorosea	NoFly, Ancora
(= *Isaria* & *Paecilomyces fumosoroseus*)	
Metarhizium anisopliae	Met52, Tick-EX

IRAC Unknown: *UNK*

azadirachtin	Azatin O, Azatin XL, Molt-X, Ornazin 3% EC, TreeAzin
*dicofol**	*Kelthane**[2]
pyridalyl	Overture 35 WP

IRAC *Unclassified*

Entomopathogenic nematodes (EN)

Heterorhabditis bacteriophera	B-Green, Exhibitline H, Larvanem, NemaShield HB, Nemasys G
Steinernema spp.	TigraNem
Steinernema carpocapsae	Carpocapsae-System, Capsanem, Casea, Exhibitline SC, Millenium, Nematac C, Sportnem-T
Steinernema feltiae	Capirel, EntoNem, NemaSys, NemaShield, Scia-rid Steinernema-System
Steinernema kraussei	Kraussei-System, Nemasys L

Horticultural, petroleum or paraffinic oils	SuffOil-X, SunSpray Ultra- Fine Spray Oil, TriTek, Ultra-Pure Oil
Potassium salts of fatty acids (insecticidal soap)	AllPro, Kopa, M-Pede
Kaolin clay	Surround WP

[1] Mention of any active ingredient or product does not imply approval, endorsement or guarantee of the products. Use pesticides only according to the directions on the label. Product labels change frequently and will include more details and specifics about potential phytotoxicity that may result in certain plant species when products are applied or used at certain rates. All product labels should be reviewed prior to treatment application. Follow all directions, precautions, and restrictions that are listed.

[2] Chemical subgroups, active ingredients, and product names that are *italicized* and indicated with an asterisk (*) are no longer labeled or available for use in the U.S. They are retained here for informational purposes only.

[#] Products indicated with a pound sign are for informational purposes only; they may not have active labels for use in turf and ornamental systems.

For additional information, contact your county Extension office, or:

Clemson University
Pee Dee Research and Education Center
2200 Pocket Road
Florence, SC 29506-9727
www.clemson.edu

UT Institute of Agriculture
UT Extension
2621 Morgan Circle
121 Morgan Hall
Knoxville, TN 37996
ut**extension.tennessee.edu**

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