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Resistance Management of Arthropod Pests in Greenhouse Production Systems

Pesticides (in this case, insecticides and miticides) provide effective management of arthropod (insect and mite) pests in greenhouse production systems. In addition to convenience and ease of application, when applied properly, pesticides provide high mortality (kill) of the most common arthropod pests including aphids, fungus gnats, leafminers, mealybugs, mites, thrips, shore flies, and whiteflies.

Temperature, relative humidity, and day length, which are associated with the greenhouse environment, can promote the growth and development of arthropod pest populations. In addition, cultural practices including watering and fertilizing contribute to the growth and development of arthropod pest populations, which are sustained by dense plantings that provide a continuous food supply. Growing horticultural crops in the same greenhouse throughout the year can result in arthropod pests being carried over from crop to crop.

Greenhouse producers have come to depend on pesticides to manage arthropod pest populations and avoid plant damage, but relying solely on pesticides may lead to the development of resistance in arthropod pest populations. Although pesticides are used widely to alleviate arthropod pest problems in greenhouse production systems, extensive use has been shown to increase the development of pesticide resistance. Greenhouse producers are encouraged to implement resistance management strategies to ensure continued effectiveness and longevity of existing pesticides.

This publication provides information to help greenhouse producers better understand pesticide resistance and outlines resistance management strategies designed to reduce the likelihood of arthropod pest populations developing resistance. Topics include pesticides (insecticides and miticides), pesticide resistance, resistance in arthropod pest populations, rotation programs, pesticide mixtures, and biopesticides.

Pesticides (Insecticides and Miticides)

Pesticide (insecticide and miticide) applications have been used to manage arthropod pest populations in greenhouse production systems for decades. In general, the arthropod pests have not changed, but the pesticides for managing them have changed due to stricter regulations governing pesticide use.

Before the 1990s, greenhouse producers might expect to have access to two or three new active ingredients each year for greenhouse use. A number of pesticides were available, which were capable of killing nearly all arthropod pests that negatively affected crop production. These broad-spectrum pesticides were not only effective against a wide range of arthropod pests, but they could be applied less frequently because of their long residual activity or persistence. Examples include aldicarb (Temik), oxamyl (Vydate), methomyl (Lannate), and bendiocarb (Dycarb/Ficam). With fewer pesticide applications, there were less opportunities for arthropod pests to pass genetic traits to their offspring that might confer resistance.

Most broad-spectrum pesticides have been discontinued and are no longer available for use in greenhouse production systems following the passage of new pesticide laws and regulations. Despite major concerns regarding toxicity to humans, acephate (Orthene), methiocarb (Mesurol) and several of the older broad-spectrum pesticides can still be used legally in greenhouse production systems.

There has been an increase in the cost and time to develop and register a new active ingredient, which is about $300 million with a development time of 7 to 10 years. As a result, fewer new active ingredients are being approved for use in greenhouse production systems. The new pesticides that are being registered are more selective, meaning they target fewer types of arthropod pests than the broad-spectrum pesticides that were available previously. Compared to broad-spectrum pesticides, the newer selective pesticides are less toxic to humans, may have minimal effects on biological control agents (e.g., parasitoids and predators), and are less harmful to the environment because of their short residual activity. Table 1 lists examples of selective pesticides. Pesticides that are less persistent may need to be applied more frequently, which can inadvertently place selection pressure on arthropod pest populations and lead to the development of resistance.

Some arthropod pest populations have already developed resistance to certain pesticides. For instance, many western flower thrips, *Frankliniella occidentalis*, populations (Figure 1) have developed resistance to spinosad (Conserve). Likewise, certain leafminer (Figure 2) and twospotted spider mite, *Tetranychus urticae*, populations (Figure 3) have developed resistance to abamectin (Avid). Spinosad and abamectin are not used as often as they were previously because of reduced effectiveness, but both pesticides may be effective when integrated into rotation programs with other pesticides.

Extensive use of the neonicotinoid class of insecticides increased the likelihood of resistance developing in the Q-biotype of the sweet potato whitefly, *Bemisia tabaci* (Figure 4). The whitefly has developed resistance to the neonicotinoid insecticides imidacloprid (Marathon), thiamethoxam (Flagship), and acetamiprid (TriStar), and to the insect growth regulators buprofezin (Talus) and pyriproxyfen (Distance). These examples demonstrate why producers should not rely exclusively on selective pesticides with similar modes of action for the management of insect pest populations.

Figure 1. Western flower thrips. (Photo: Raymond Cloyd)

Pesticide Resistance

Resistance is the ability of some individuals in an arthropod pest population to survive an application of a pesticide. When resistance develops, the pesticide no longer kills a sufficient number or percent (>90%) of targeted individuals to prevent plant damage. Resistance develops at the population level and is an inherited trait. The arthropod pests that survive can pass genetic traits to their offspring, thus incorporating more resistant genes to the gene pool. The genetic composition of an arthropod pest population changes over time in response to selection pressure by a pesticide. Pesticide applications kill susceptible individuals in an arthropod pest population, leaving individuals with traits that enable them to survive. The effect of pesticides that favor survival of resistant individuals with certain genetic traits is known as selection pressure. Selection pressure for resistance to pesticides increases in relation to application frequency, especially when pesticides with the same mode of action are applied in succession. The frequency with which resistant genes occur in an arthropod pest population determines the level of resistance within a specific arthropod pest population.

Each successive pesticide application places additional selection pressure on arthropod pest populations, which may further increase the frequency of resistant individuals (Figure 5). Pesticide resistance develops in arthropod pest populations through one of two mechanisms, either metabolic detoxification or physiological changes. *Metabolic resistance* is the breakdown of the pesticide active ingredient inside the insect body. The metabolic process is triggered by specific enzymes that detoxify or convert the active ingredient into a nontoxic form before the active ingredient is excreted with waste from the body. *Physiological resistance* involves alterations in the site targeted by the

Figures 2 and 3. Leafminer adults (left) and twospotted spider mites (right). (Photo: Raymond Cloyd)

Figure 4. Sweetpotato whitefly adult. (Photo: Raymond Cloyd)

pesticide active ingredient, which decreases sensitivity of the target site in the central nervous system.

The following biological factors in arthropod pest populations contribute to the development of resistance:

- Short generation time (number of individuals progressing from egg to adult)
- Multiple generations per season or cropping cycle
- High female reproduction
- Feed on a broad range of host plants, which increases exposure to pesticide applications

The most common method for delaying the onset of resistance is to alternate the use of pesticides with different modes of action. Before discussing specific strategies, greenhouse producers need to understand how resistance develops in arthropod pest populations associated with greenhouse production systems.

Resistance in Arthropod Pest Populations

Resistance develops at the population level, with surviving individuals passing genetic traits to their offspring, and thereby increasing the frequency of resistant genes in the gene pool. Resistance can vary from one greenhouse to another based on pesticide use. Global movement of plant material and the importation of arthropod pest populations with resistant traits that are later exposed to pesticides with similar modes of action can increase the rate of resistance development.

Arthropod pests of greenhouse-grown horticultural crops are not predisposed to develop resistance to pesticides but may encounter intense selection pressure due to frequent pesticide applications (Figure 6), which increases the potential for the development of resistance. Arthropod pests such as aphids, mites, thrips, and whiteflies have developed resistance to a wide range of pesticides in the chemical classes including organophosphates, carbamates, pyrethroids, macrocyclic lactones, and spinosyns. In fact, more than 550 insect pest species have developed resistance to one or more insecticides over the past 50 years.

Many arthropod pests encountered in greenhouse production systems have short life cycles (egg to adult) and females have high reproductive rates, both of which contribute to the increased likelihood of resistance developing in arthropod pest populations. Furthermore, in greenhouse production systems arthropod pests can breed year-around with many generations occurring simultaneously, which may warrant more frequent pesticide applications. In general, most pesticides are applied every 5 to 7 days. Despite frequent applications, a certain number of individuals may

Figure 5. Every time a pesticide is applied selection pressure is placed on arthropod pest populations. (Photo: Raymond Cloyd)

Figure 6. Frequent pesticide applications can result in arthropod pest populations developing resistance. (Photo: Raymond Cloyd)

survive because they are not in susceptible life stages (eggs or pupae) or do not come in contact with spray residues. Any surviving individuals that may be resistant can then breed with other resistant survivors to produce a population of highly resistant individuals that eventually become fully resistant to the pesticide after nearly all susceptible individuals in the population are killed.

Arthropod pests such as the twospotted spider mite (Figure 7) that remain on plants to feed may develop resistance faster than thrips and whiteflies, which are more mobile. Resistance develops rapidly because the intense selection pressure associated with frequent pesticide applications reduces the number of susceptible individuals

Figure 7. Localized or isolated populations of arthropod pest populations can develop resistance to pesticides. (Photo: Raymond Cloyd)

remaining to breed with resistant individuals. Moreover, resistance can develop more rapidly in greenhouses because there is not an influx of susceptible individuals from the outside during the growing season.

Rotation Programs

Applying pesticides with the same mode of action repeatedly increases selection pressure on arthropod pest populations, which can increase the development of resistance. Therefore, alternating pesticides with different modes of action will preserve the effectiveness of pesticides and increase their longevity. The means by which a pesticide negatively affects the target arthropod pest is referred to as the mode of action. Pesticides applied to manage arthropod pest populations in greenhouses may target a specific-site or multiple sites. Most specific-site mode of action pesticides target specific sites in the central nervous system. Pesticides that target a variety of sites or possess more than one mode of action have multiple-site modes of action.

The Insecticide Resistance Action Committee (IRAC) maintains a list of insecticides and miticides, which are grouped by mode of action. The number and letter designations for each can be found at *www.irac-online.org* along with information that will help greenhouse producers develop appropriate rotation programs to manage arthropod pest populations during the growing season. The mode of action of a pesticide may be represented as a number or a number and letter on the product label (Figure 8). Greenhouse producers should read the label making sure to rotate common names (active ingredient) and not trade or brand names as products with different trade names may contain the same active ingredient.

Relying on one or more pesticides with similar modes of action to manage a particular arthropod pest population will increase selection pressure and contribute to the development of resistance. The best way to delay the onset of resistance is to rotate pesticides with different modes of action. Greenhouse producers should use one pesticide for approximately 2-3 weeks, or for the duration of one generation of an arthropod pest population, before switching to a pesticide with a different mode of action. Do not rotate pesticides with different modes of action within a single arthropod pest generation. Many pesticide labels include information to help greenhouse producers develop appropriate rotation programs. For instance, the product label may provide instructions for using the product as a component of a resistance management strategy by indicating the number of applications that can be made before switching to a pesticide with a different mode of action (Figure 9).

Greenhouse producers should avoid exclusive use of specific-site mode of action pesticides that target a single mechanism or biological pathway, as this may lead to the development of resistance in an arthropod pest population. The use of pesticides that act on multiple target sites or have multiple-site modes of action may reduce the probability of arthropod pest populations developing resistance. Pesticides with multiple-site modes of action include: insecticidal soap (potassium salts of fatty acids); horticultural (petroleum, mineral, or neem-based) oils; and entomopathogenic fungi (*Beauveria bassiana* and *Isaria fumosorosea*).

Similarly, insect growth regulators with different modes of action should be rotated. Insect pests such as aphids and whiteflies have developed resistance to a number of insect growth regulators. Three modes of action associated with insect growth regulators are chitin synthesis inhibitors (buprofezin, diflubenzuron and novaluron); juvenile hormone mimics (kinoprene and pyriproxyfen); and ecdysone receptor agonists/antagonists (azadirachtin and methoxyfenozide).

Greenhouse producers may need to adjust rotation programs during the growing season. For example, as temperatures increase in late spring through early fall, the life cycle (egg to adult) of arthropod pests is shorter. Temperatures greater than 75°F (24°C) reduce the development time and generations may overlap. When different life stages (eggs, larvae/nymphs, pupae, and adults) are present simultaneously, more frequent pesticide rotations and repeated pesticide applications will be required. The frequency of rotating pesticides with different modes of action can vary depending on the time of year. For instance, during winter, pesticides may not have to be rotated as frequently when arthropod pest life cycles take longer to complete due to lower temperatures and shorter day lengths. Examples of rotation programs for the major arthropod pests of greenhouse-grown horticultural crops are presented in Table 2.

Pesticide Mixtures

A pesticide mixture involves mixing or combining two or more pesticides into a single spray solution, which allows greenhouse producers to manage multiple arthropod pests at the same time, thus reducing labor costs. When applied to greenhouse-grown horticultural crops, the pesticide mixture exposes individuals in an arthropod pest population to each of the pesticides simultaneously.

It is still unclear if pesticide mixtures are more effective than other application methods in delaying the onset of resistance. Greenhouse producers may wrongly assume that two or more pesticides applied at different intervals offer the same advantage as a pesticide mixture. The assumption is incorrect because each individual arthropod pest in a population has not been exposed to a lethal dose or concentration of each pesticide. In fact, resistance may evolve more rapidly than would occur with a pesticide mixture.

Figure 8. Pesticide products contain information about the mode of action based on the IRAC group designation. (Photo: Raymond Cloyd)

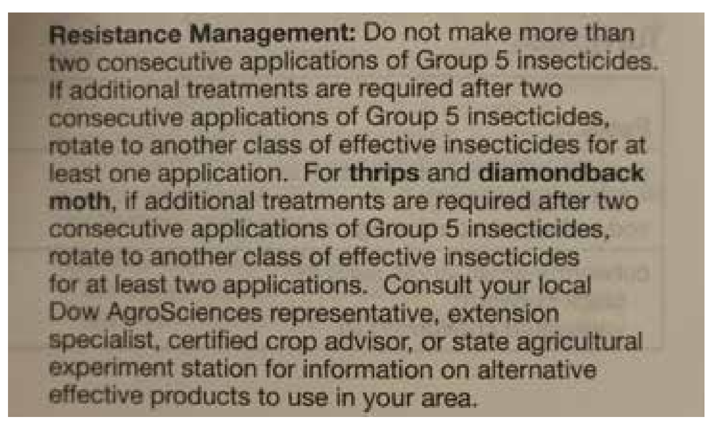
Resistance Management: Do not make more than two consecutive applications of Group 5 insecticides. If additional treatments are required after two consecutive applications of Group 5 insecticides, rotate to another class of effective insecticides for at least one application. For **thrips** and **diamondback moth**, if additional treatments are required after two consecutive applications of Group 5 insecticides, rotate to another class of effective insecticides for at least two applications. Consult your local Dow AgroSciences representative, extension specialist, certified crop advisor, or state agricultural experiment station for information on alternative effective products to use in your area.

Figure 9. Pesticide labels include information on resistance management . (Photo: Raymond Cloyd)

Mixing pesticides with different modes of action can delay the onset of resistance developing in an arthropod pest population because the mechanism(s) for resisting the pesticide mixture (e.g., metabolic detoxification by way of enzymes or physiological changes leading to target site insensitivity) may not be present in the arthropod pest population. In addition, individuals in the arthropod pest population may have more difficulty developing resistance to several modes of action simultaneously, and individuals resistant to one or more pesticides would likely succumb to the other pesticide in the mixture if pesticides with different modes of action are mixed together.

Pesticide mixtures may alleviate the potential for resistance to develop in an arthropod pest population. For instance, pesticide mixtures that combine pesticides with specific-site modes of action with those having multiple-site modes of action may delay the onset of resistance developing. However, pesticide mixtures with different but specific-site modes of action may lead to arthropod pest populations developing resistance to the different pesticides.

The continued use of the same pesticides in a mixture may lead to the development of resistance to both modes of activity. Greenhouse producers should use different pesticides with distinct modes of action to mitigate the potential for resistance. Once arthropod pest populations have acquired resistance to two pesticides with different modes of activity, they become extremely difficult to manage, which limits pesticide options.

The effects of pesticide mixtures on arthropod pest populations can vary depending on species, strain, and biotype differences associated with mechanisms of resistance present in arthropod pest populations. Pesticide mixtures will only succeed in delaying the onset of resistance if there is no cross resistance. Cross resistance refers to a single resistance mechanism that confers resistance to pesticides in the same chemical class and/or pesticides with similar modes of action.

Biopesticides

Biopesticides are a class of pesticides derived from natural materials such as plants, bacteria, animals, and minerals. The three major classes of biopesticides are microbial pesticides, plant-incorporated protectants, and biochemical pesticides.

Microbial pesticides consist of a microorganism as the active ingredient (e.g., fungus, bacterium, virus, or protozoa), which is highly selective against specific target insect pests.

Plant-incorporated protectants are substances produced by plants that may have negative effects on arthropod pests.

Biochemical pesticides are nontoxic natural substances such as insect sex pheromones that interfere with mating or scented plant extracts that attract insect pests to traps.

Microbial pesticides used in greenhouse production systems are derived from bacteria and fungi. Bacteria must be consumed (stomach poison) by the insect to induce mortality, whereas fungi directly penetrate the insect cuticle (skin) and can initiate an infection. The microbial insecticides registered for use in greenhouse production systems include the fungi *Beauveria bassiana* Strain GHA (BotaniGard), *Isaria fumosorosea* Apopka Strain 97 (Ancora), and *Metarhizium brunneum* (Met52); and the bacteria *Bacillus thuringiensis* subsp. *kurstaki* (Dipel), *B. thuringiensis* subsp. *israelensis* (Gnatrol), *Saccharopolyspora spinosa* or spinosad (Conserve), and *Chromobacterium subtsugae* Strain PRAA4-1T (Grandevo).

Microbial pesticides should be integrated into rotation programs and/or used in pesticide mixtures to delay the onset of resistance in arthropod pest populations. Pesticides with specific-site modes of action are more likely to result in the development of resistance because some individual arthropod pests may be able to detoxify the active ingredient. However, arthropod pests may have more difficulty developing resistance to microbial pesticides that have multiple-site modes of action.

Greenhouse producers should integrate pesticides with specific-site modes of action and microbial pesticides with multiple-site modes of action into rotation programs to prolong the effectiveness and longevity of available pesticides instead of solely using pesticides with specific-site modes of action. Pesticide mixtures that include microbial pesticides can help alleviate the potential for resistance developing in an arthropod pest population. For instance, the use of pesticide mixtures that include pesticides with specific-site modes of action along with microbial pesticides that have multiple-site modes of action can mitigate development of resistance in arthropod pest populations.

Furthermore, mixing microbial pesticides with another active ingredient may increase the toxicity of the pesticide. For example, mixing the entomopathogenic fungus, *Metarhizium brunneum* (Met52), with a product containing azadirachtin (e.g., Azatin, Ornazin, and Molt-X) can increase the mortality of insect pests such as the western flower thrips compared to the mortality that would result if the two active ingredients were applied separately. Azadirachtin is an insect growth regulator, more specifically, an ecdysone antagonist, which inhibits molting. A delay in the molting process gives the entomopathogenic fungus, *Metarhizium brunneum*, time to penetrate the cuticle and infect the insect pest before shedding the old cuticle (ecdysis). The more time the fungus has to penetrate the cuticle and initiate an infection, the greater the chances that the fungus will kill the insect pest.

Conclusion

Resistance management strategies are important in preserving the long-term effectiveness of registered pesticides (in this case, insecticides and miticides) and providing greenhouse producers with options for managing arthropod pest populations. If arthropod pest populations develop resistance, then pesticide options become limited. Therefore, pesticides should only be applied when arthropod pest populations reach levels that can result in plant damage. Greenhouse producers should implement rotation programs that incorporate pesticides with different modes of action to reduce the risk of resistance developing in arthropod pest populations.

Table 1. Common name, trade name, and target arthropod pests of selective pesticides (insecticides and miticides) registered for use in greenhouse production systems.

Common name (active ingredient)	Trade name	Targeted arthropod pests
Abamectin	Avid	Aphids, Mites, and Thrips
Acequinocyl	Shuttle O	Mites
Afidopyropen	Ventigra	Aphids, mealybugs, and whiteflies
Bacillus thuringiensis subsp. *kurstaki*	Dipel/Thuricide	Caterpillars
Bifenazate	Floramite	Mites
Buprofezin	Talus	Leafhoppers, mealybugs, and whiteflies
Clofentezine	Novato	Mites
Cyantraniliprole	Mainspring	Aphids, thrips, and whiteflies
Cyflumetofen	Sultan	Mites
Etoxazole	TetraSan	Mites
Fenpyroximate	Akari	Mealybugs, mites, and whiteflies
Hexythiazox	Hexygon	Mites
Methoxyfenozide	Intrepid	Caterpillars
Novaluron	Pedestal	Caterpillars, thrips, and whiteflies
Pymetrozine	Endeavor	Aphids and whiteflies
Pyridaben	Sanmite	Mites and whiteflies
Pyridalyl	Overture	Caterpillars and thrips
Pyriproxyfen	Distance/Fulcrum	Fungus gnats, shore flies, and whiteflies
Spinosad	Conserve	Caterpillars, leafminers, and thrips
Spiromesifen	Savate	Mites and whiteflies

Table 2. Rotation programs for arthropod (insect and mite) pests of greenhouse-grown horticultural crops. The rotation programs for each arthropod pest are based on an eight-week spray application schedule using four pesticide (insecticides or miticide) products (trade names) with different modes of action.

Pest			
Aphids			
Weeks 1 and 2	***Weeks 3 and 4***	***Weeks 5 and 6***	***Weeks 7 and 8***
Mainspring	Hachi-Hachi	Kontos	Rycar
Marathon II	Aria	SuffOil-X	Ventigra
Mealybugs			
Weeks 1 and 2	***Weeks 3 and 4***	***Weeks 5 and 6***	***Weeks 7 and 8***
TriStar	Rycar	Enstar	SuffOil-X
M-Pede	Ventigra	Talus	TriStar
Thrips			
Weeks 1 and 2	***Weeks 3 and 4***	***Weeks 5 and 6***	***Weeks 7 and 8***
Conserve	Overture	Avid	Pylon
Pylon	Mainspring	Mesurol	XXpire
Twospotted Spider Mite			
Weeks 1 and 2	***Weeks 3 and 4***	***Weeks 5 and 6***	***Weeks 7 and 8***
Avid	Floramite	Savate	Pylon
Kontos	TetraSan	Sanmite	SuffOil-X
Whiteflies			
Weeks 1 and 2	***Weeks 3 and 4***	***Weeks 5 and 6***	***Weeks 7 and 8***
Distance/Fulcrum	Mainspring	Pedestal	TriStar
Safari	Talus	Altus	Endeavor

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