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Resistance Management of *Arthropod Pests*

Nursery and greenhouse managers must judiciously use pesticides with different modes of action and detoxification in order to avoid resistance among arthropod pest populations, as well as preserve the effectiveness of currently available pesticides.

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Resistance management is a strategy designed to preserve or sustain the effectiveness of pesticides. Although the concept of resistance is usually associated with arthropod (insect and mite) pests, there are a number of plant pathogens that have demonstrated resistance (such as gray mold [*Botrytis cinerea*]) to certain fungicide classes. In addition, many weed species are resistant to pre- and postemergent herbicides.

This article will focus on resistance management of plant-feeding arthropods. However, avoiding resistance is just as important in disease and weed management.

Resistance by arthropod pests. Arthropod pests in ornamental production systems (greenhouses and nurseries) are principally managed with pesticides (insecticides and miticides). Arthropod pests possess the inherent ability to evolve or adapt to various environmental and human disturbance factors, such as pesticide applications. Therefore, continual reliance on pesticides eventually leads to resistance, which is the genetic ability of some individuals in an arthropod pest population to survive pesticide exposure. In other words, the pesticide no longer kills a sufficient number of individuals in the arthropod pest population to be considered effective.

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When pest-control materials, such as insecticides and miticides, are applied too frequently, it leads to an increased likelihood of resistance occurring in an arthropod pest population.

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Currently, more than 520 insect species have developed resistance to insecticides during the past 50 years, with an average of 13 new resistance cases per year.

Resistance is an international concern with expanding global trade of plant material, which not only can spread arthropod pests, but may also spread resistance genes of the pests they harbor. Resistance is an inherited trait.

Evolution of resistance in a population depends on existing genetic variability that permits survival of some individuals when exposed to a pesticide. Surviving individuals transfer traits genetically to the next generation, thus enriching the gene pool with resistance genes. The "selection pressure" — the proportion of the population killed by a pesticide — is the main factor, along with genetic variation in the arthropod pest for susceptibility to the pesticide, which influences the evolution of resistance. Every time an arthropod pest population is exposed to a pesticide, it results in selection for resistance, thus increasing the frequency or proportion of resistant genes within an arthropod pest population.

Traits providing adaptive advantage include rare versions of genes that diminish sensitivity to a particular pesticide, or altered gene expression that results in amplification of commonly existing genes. In rare instances, no genetic variation may occur (such as resistance to horticultural oil that would require a defense against suffocation), which blocks resistance development. Furthermore, the life stages (egg, larvae and adult) may vary in susceptibility based on the presence of particular resistance mechanisms.

The speed of resistance developing in an arthropod pest population is dependent primarily on two biological factors: short generation time and high female fecundity. In addition, some arthropod pests, including the twospotted spider mite (*Tetranychus urticae*) and western flower thrips (*Frankliniella occidentalis*), have haplodiploid breeding systems that accelerate the rate of resistance development. Genes associated with resistance are fully expressed in haploid (single set of chromosomes) males in haplodiploid species, whereas with entirely diploid (double set of chromosomes) species, resistance may be partially hidden as recessive or co-dominant traits.

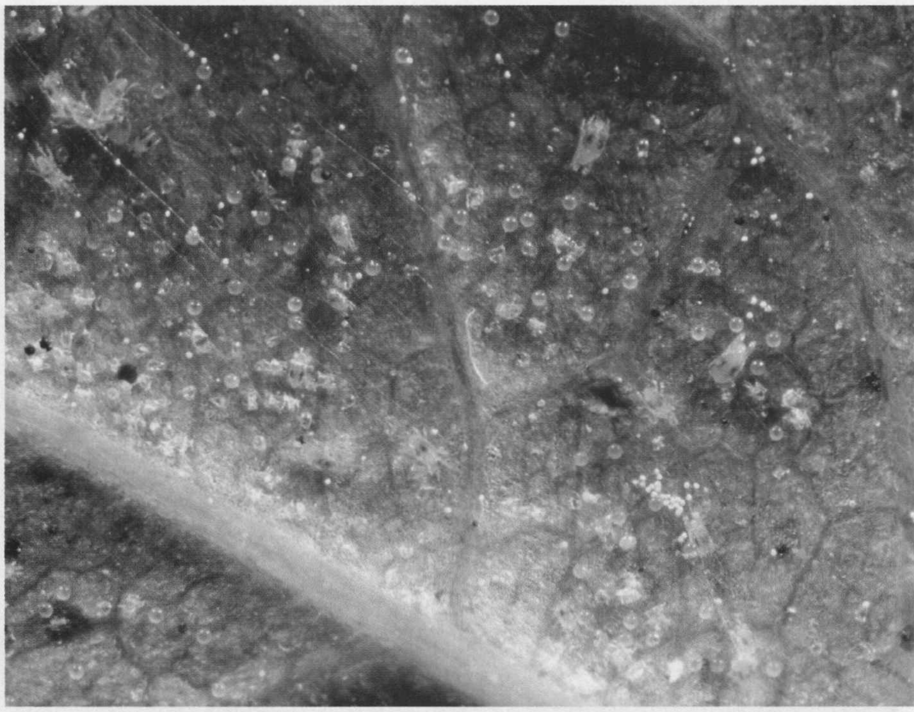
Genes for resistance typically occur at a very low frequency in an arthropod pest population before any pesticide is applied. An individual does not become resistant, but due to frequent applications of a given pesticide over multiple generations, susceptible individuals are removed from the population and resistant individuals remain to reproduce. This results in an arthropod pest population that can no longer be controlled with a given pesticide.

Resistance may also develop due to the movement of arthropod pests within and into greenhouses and nurseries. There are three ways that pest immigration enhances resistance. First, migration from other crops within the greenhouse or nursery — or between greenhouses and nursery blocks — increases the likelihood that the arthropod pest population has been exposed to additional pesticide applications. Second, receiving plants from a distributor with arthropod pests that have been previously exposed to pesticides may enhance the prospect of resistance developing, as a large percentage of these arthropod pests may already possess genes for resistance. Finally, arthropod pests that enter greenhouses or nurseries from field- or vegetatively grown crops may have been exposed to agricultural pesticides that are similar to those used in greenhouses and nurseries.

Resistance mechanisms. Different mechanisms can confer resistance in various populations of the same species of an arthropod pest, and multiple resistance mechanisms may co-exist in the population, which is called "polyfactorial resistance." The mechanisms of resistance are: metabolic, physical, physiological, behavioral and natural.

Metabolic resistance: This is the breakdown of the active ingredient by the arthropod pest. When the pesticide enters the body, enzymes attack and detoxify or convert the active ingredient into a nontoxic form. Detoxifying enzymes convert insecticides (which are hydrophobic or "water hating") to more hydrophilic ("water loving") and less biologically active compounds that are eliminated via excretion.

A number of enzymes may be involved, including hydrolases (carboxylesterases), glutathione *S*-transferases and cytochrome P450 monooxygenases. These are large families of enzymes that are capable of metabolizing unusual plant chemicals, insect hormones and pesticides. The levels of these enzymes are not static in arthropod pests: They change during development (which can make some life stages more susceptible to a pesticide than others) and also upon expo-



The haplodiploid breeding system of the twospotted spider mite (*Tetranychus urticae*) may accelerate the rate of resistance developing in arthropod pest populations.

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sure to various chemicals through a process called enzyme induction.

Physical resistance: This is a change or alteration in the cuticle (skin) that reduces or delays penetration of the pesticide. Delayed penetration through the cuticle reduces the concentration of insecticide at the target site and prevents overloading the insects' detoxification system.

Physiological resistance: This is also known as "target site insensitivity." The interaction between the pesticide and its target is similar to a key (the toxin) fitting into a lock (the target site). Decreased binding associated with physiological resistance is analogous to the lock having been changed so that the key no longer fits, and consequently, the pesticide is no longer effective.

Examples of this kind of resistance occur in the organophosphate, carbamate and pyrethroid chemical classes. Insects may evolve different means to decrease susceptibility to organophosphate and carbamate insecticides, including reduced sensitivity of acetylcholinesterase (AChE; an enzyme in the central nervous system), increased activity of AChE or overproduction of AChE. Additionally, insects may possess what is known as "knockdown resistance." In this case, insects have reduced sensitivity of the nervous system to pyrethroid-based insecticides — such as bifenthrin, cyfluthrin, permethrin, fenpropathrin, fluvalinate and lambda-cyhalothrin — due to modified sodium channels of nerve axons, which is the target site for pyrethroid-based insecticides.

Behavioral resistance: This is when arthropod pests avoid contact with a pesticide. One behavior is hiding in locations, such as the terminal growing points, which may be difficult for the pesticide to penetrate. Another behavior is loss of a leg that has contacted insecticide residues. Altered behaviors may allow arthropod pests to avoid contact and thus exposure to pesticides.

Natural resistance: This describes the lack of susceptibility to a toxin that is pre-existing and does not result from repeated exposure of an arthropod pest population to a pesticide. This may be due to any of the previously described metabolic, physical, physiological or behavioral traits, and includes life stages not susceptible to a pesticide. For example, most contact and systemic insecticides and/or miticides are not effective against the eggs and pupae. Another example is the natural resistance of fly larvae to *Bacillus thuringiensis* (*Bt*) *kurstaki*, which is a soil-derived bacterium specifically toxic to caterpillars.

There are two additional mechanisms associated with resistance: cross-resistance and multiple resistance. Cross-resistance involves insensitivity to pesticides with similar modes of action or in the same chemical class. Multiple resistance is when an arthropod pest population is resistant to pesticides with different modes of action or across chemical classes. Multiple resistance is a consequence of the arthropod pest population possessing more than one defense mechanism against a particular class or mode of action, or one mechanism coping with unrelated pesticides. Because resistance often involves more than one adaptive mechanism and often several detoxification enzymes, intensive selection with any pesticide can result in adaptations that will make cross-resistance more likely (as is often observed with pyrethroids) and also increase the risk of multiple resistance. Therefore, cross-resistance and multiple resistance are not necessarily distinct phenomena.

Resistance factors. Factors that may influence the rate of resistance development in arthropod pest populations can be divided into operational factors, which are under the control of greenhouse or nursery managers, and biological factors, which are intrinsic to the arthropod pest population.

Operational factors include:

- length of exposure to a single pesticide (pesticide residue characteristics);
- frequency of pesticide applications;
- dosage (use rate) of pesticide applied;
- spray coverage (nonuniform deposition on leaves or in growing medium);
- applying pesticides when the most susceptible life stages, such as larva, nymph and adult, are absent;
- previous history of pesticide use;
- relatedness of a pesticide to those that have previously been applied; and
- presence or absence of refuge sites or hiding places.

Biological factors include:

- time to complete one generation (egg to adult);
- fecundity (numbers of offspring produced per generation);
- arthropod pest mobility (winged adults disperse to mate, feeding in protected habitats);
- host range (a wide range of hosts preadapt arthropod pests to detoxify pesticides);
- mobility of individuals;
- genetic system (parthenogenesis, haplodiploid or sexual reproduction); and
- expression of resistance trait (monogenic versus multigenic; recessive versus dominant).

The stability of resistance in an arthropod pest population depends on:

- the immigration of susceptible individuals, which may reduce gene frequency for resistance in the arthropod pest population through breeding;
- use of biological control, which may counteract resistance by removing survivors following a pesticide application; and
- fitness costs for possessing resistance traits.

If the resistance trait only enhances

survival under continual pesticide exposure (such as *Bt* resistance), then when selection (pesticide exposure) ceases, individuals expressing nonresistance traits are able to survive better, reproduce faster and/or have more offspring. As such, within a few generations, susceptibility may be restored.

Greenhouse conditions can increase the rate of resistance developing in an arthropod pest population. Environmental parameters, such as temperature and relative humidity, are typically conducive for rapid arthropod pest development and reproduction. The greenhouse generally encloses arthropod pests and restricts susceptible individuals from migrating into the population. Therefore, resistant individuals within an arthropod pest population are dominant and remain in the greenhouse to breed, whereas susceptible individuals from areas not treated with a pesticide are unable to enter and hybridize with resistant arthropod pests.

In addition, biological control agents or natural enemies, such as parasitoids and predators, are often absent and cannot immigrate into greenhouses. Finally, intensive, year-round production in many greenhouses and nurseries throughout the US provides a continuous food supply for arthropod pests, and this often results in frequent exposure to pesticide applications.

Resistance management. Resistance management primarily involves judicious selection and accurate application of pesticides and their integration with other regulation strategies consistent with basic pest-management philosophy. This is the most effective way of avoiding resistance. Because resistance is genetically based, it is the frequency of resistance in an arthropod pest population that a greenhouse or nursery producer attempts to manage in a resistance-management program.

Below are generalized guidelines to help minimize arthropod pest populations from developing resistance to any pesticide.

- Scout crops regularly to appropriately time applications of pesticides to target the most susceptible life stages (larvae and/or nymphs and adults).
- Implement proper cultural (water and fertility) and sanitation (weed removal) practices.
- If feasible, screen greenhouse openings to prevent migrations of insect pests into greenhouses.
- Implement the use of biological control agents or natural enemies.
- Use synergists when applying pesticides to inhibit enzymes involved in detoxifi-

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Pesticide rotation schemes

The following are examples of rotation schemes associated with pesticides — based on the active ingredient — that have dissimilar modes of activity against various arthropod pests:

- *Aphids*: pymetrozine–>imidacloprid–> petroleum oil–>acephate
- *Thrips*: spinosad–>chlorfenapyr–> abamectin–>pyridalyl
- *Twospotted spider mite*: bifenazate–>chlorfenapyr–> pyridaben–>etoxazole
- *Whiteflies*: dinotefuran–>pyriproxyfen–> spiromesifen–>buprofezin
- *Mealybugs*: acetamiprid–>acephate–> potassium salts of fatty acids–> kinoprene
- *Fungus gnats*: pyriproxyfen–>cyromazine–> chlorfenapyr–>diflubenzuron
- *Scales*: potassium salts of fatty acids–> petroleum oil–>acetamiprid–> acephate

cation (be sure to read the label to determine if a synergist has already been incorporated into the formulation). Certain demethylation inhibitor fungicides and plant growth regulators may act as synergists by blocking the same enzymes as the conventionally used piperonyl butoxide synergist. However, because arthropod pests may counteract the presence of synergists through enzyme induction, the effects of synergists may only be temporary. Certain insecticides may also be used as synergists when mixed together. For example, organophosphate insecticides block carboxylesterase enzymes that sometimes metabolize certain pyrethroids.

- Rotate pesticides with different modes of action and/or different modes of detoxification.
- Use pesticides with multiple modes of activity, such as insect growth regulators, insecticidal soap (potassium salts of fatty acids), horticultural oils (paraffinic, petroleum-based or methylated seed oils), selective feeding blockers (inhibitors), beneficial bacteria and fungi, and microorganisms.

Mode of action or mode of activity refers to the specific target affected in an arthropod pest (such as the sodium channel of the nerve axon, oxidative phosphorylation or juvenile hormone). The classification of an insecticide or miticide is now listed by its IRAC (Insecticide Resistance Action Committee) designation on the label.

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Similar to the twospotted spider mite (*Tetranychus urticae*), western flower thrips (*Frankliniella occidentalis*) has a haplodiploid breeding system that results in an accelerated rate of resistance when exposed to frequent applications of pest-control materials.

In order to alleviate the possibility of an arthropod pest population developing resistance, it is important to design rotation programs that involve using pesticides with different modes of activity (from different IRAC groups) — not chemical classes. The reason for this is that some chemical classes have similar modes of activity. For example, organophosphates and carbamates — despite being different chemical classes — have identical modes of activity. These chemical classes block the action of AChE — an enzyme that deactivates acetylcholine (ACh) — thus allowing nerve signals to continue, which results in the total loss of nerve functions and, eventually, paralysis. So, for example, using acephate for two consecutive spray applications during a generation and then switching to methiocarb does not constitute a proper rotation scheme.

Similarly, although acequinocyl, pyridaben and fenpyroximate are in different chemical classes — naphthoquinone, pyridazinone and phenoxypyrazole, respectively — all three are active on the mitochondria electron transport chain (responsible for energy production) by inhibiting nicotinamide adenine dinucleotide hydride (NADH) dehydrogenase (complex I), acting on the NADH-coenzyme quinone reductase site or binding to cytochrome bc_1 (complex III), resulting in blockage of adenosine triphosphate production. Therefore, these materials should never be used in succession.

The neonicotinoid chemical class contains a number of insecticides, including imidacloprid, thiamethoxam, acetamiprid and dinotefuran. All the neonicotinoid-based insecticides have similar modes of action, which involve binding of the active ingredient to the postsynaptic nicotinergic ACh receptors, causing irreversible blockage. So, it is essential to avoid using them in succession as this may increase selection pressure, resulting in resistance to this class of insecticides. It is recommended to use an insecticide with a different mode of activity before using a neonicotinoid-based insecticide.

Because resistance can develop due to enhanced metabolic conversion of insecticides, the rotation schemes based on the IRAC groupings cannot be considered a fail-safe approach for avoiding resistance as it only takes into account mode of action — not mode of detoxification. Examples of multiple resistance have demonstrated that elevated general detoxification capabilities resulting from intensive selection pressure with one insecticide can jeopardize the effectiveness of many other insecticides, including those associated with different IRAC groupings.

Another essential strategy is to rotate pesticides with specific modes of activity with those having nonspecific or multiple modes of activity. This will minimize the possibility of an arthropod pest population developing resistance. However, it is also important to rotate insect growth regulators with different modes of action because certain insect pests have demonstrated resistance to a number of insect growth regulators.

It is important to rotate common names (active ingredient) — not trade or brand names. For example, both Azatin and Ornazin — despite having different trade names — contain the same active ingredient: azadirachtin. In general, rotate different modes of activity every two to three weeks, or within one to two arthropod pest population generations. However, this will depend on the time of year as temperature influences the duration of the life cycle (egg to adult).

High temperatures that typically occur during the summer months shorten the developmental time of most of the major arthropod pests of greenhouses and nurseries, including aphids, thrips, whiteflies, caterpillars, beetles and spider mites. This often leads to overlapping generations with variable age structures (eggs, larvae/nymphs, pupae and/or adults) present simultaneously. More frequent pesticide applications are required, and they must be rotated more often. In contrast, during the winter months, the development time of greenhouse and nursery arthropod pests is extended due to the cooler temperatures and shorter day lengths, which means that pesticides may not have to be rotated as frequently.

Finally, tank mixing may delay resistance developing within arthropod pest populations because the mechanisms required to resist pesticide mixtures may not be widespread or exist in arthropod pest populations. It may be difficult for individuals in the arthropod pest population to develop resistance to several modes of action simultaneously. Arthropod pests in the population that are resistant to one or more pesticides would likely succumb to the other pesticide in the mixture. However, this approach also risks selecting for detoxification mechanisms that may permit survival to both pesticides.

The rotation of pesticides will only be effective in delaying the development of resistance if the pesticides used select different resistance mechanisms. For example, metabolic resistance may confer resistance to pesticides in different chemical classes that have different modes of action. Thus, rotation schemes should encompass as many pesticides with different modes of action and detoxification as possible.

Combining resistance management and IPM. The key to converting from a pesticide-management approach to IPM usually requires greater reliance on biological control and discontinuing the use of broad-spectrum pesticides (especially organophosphates, carbamates and pyrethroids). Careful use of selective pesticides may work in concert with naturally occurring or introduced parasitoids and/or predators to maintain arthropod pest populations at nondamaging levels.

Ornamental crops grown in greenhouses and/or nurseries often have very dense canopies, which may make complete spray coverage difficult. This may lead to a situation where the outer part of the plant canopy is thoroughly sprayed, but a refuge remains unsprayed in the plant interior, which allows arthropod pests to recolonize the outer foliage. When selective pesticides are employed, natural enemies are preserved, which allows them to deal with the remaining arthropod pest population in the unsprayed refuges. This avoids the buildup of pesticide resistance among arthropod pest populations by eliminating any survivors through parasitism or predation. As such, effective

Tank mixing may delay resistance developing within arthropod pest populations because the mechanisms required to resist pesticide mixtures may not be widespread or exist in arthropod pest populations.

arthropod pest suppression can be achieved without the need to ensure complete spray coverage.

Unfortunately, this system cannot be established under circumstances where long-residual, broad-spectrum pesticides have previously been applied, as these pesticides are generally more toxic to natural enemies than arthropod pests. However, applying systemic insecticides, which are taken up by plant roots, may sometimes be used in conjunction with natural enemies because residues are internal to the plant. This limits direct exposure of natural enemies to the insecticide. Finally, horticultural oils are valuable for integrated management of spider mites — all life stages (eggs, larvae, nymphs and adults) are susceptible to suffocation by oil, whereas predatory mites in Phytoseiidae can tolerate application rates of up to 1 percent horticultural oil.

It is important that greenhouse and nursery producers exercise judicious use or proper stewardship of pesticides with different modes of action and detoxification in order to avoid or overcome the problem of resistance, as well as preserve the longevity of currently available pesticides. Furthermore, remember that the failure to control or regulate arthropod pest populations is not always due to resistance.

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