Fungicides and Biocontrols for Management of Florists' Crops Diseases

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Abstract

Florists' crops are prone to numerous diseases caused by fungi, oomycetes, bacteria, nematodes, viruses, viroids, phytoplasmas, and abiotic agents. Since consumers prefer and typically require high quality aesthetics for florists' crops, any marring due to pathogens will greatly reduce crop value if not render it nonsalable. Continued grower livelihood requires successful management of pathogens using all available components of integrated disease management. In this chapter, we will briefly describe the current development pathway for chemical and biological tools to manage diseases, guidelines for use including considerations for resistance management, and application technology. We will highlight current fungicides and biopesticides registered in the United States to ameliorate diseases of florists' crops.

Keywords

Fungicides • Bactericides • Nematicides • Chemicals • Biologicals • Rotations • Tank mixes • Disease management

Contents

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1 Introduction

Environmental horticulture crops (EHCs) are one of the highest value-per-acre specialty crop industries in the United States (US) farm sector at $20.34 billion in US Gross Domestic Product (GDP) (Hodges et al. 2015). Broadly defined, EHCs are plants grown for placement into residential and commercial landscapes, interiorscapes, arboreta, parks, sports fields, and recreational areas. These plants are utilized and valued for numerous nonedible attributes, including removal of pollutants from air and water, CO_2 sequestration, reduction of urban heat islands and soil erosion, increased property values, pollinator services, recreational and relaxation activities, and aesthetic qualities. Florists' crops are a subset of environmental horticulture crops typically although not exclusively sold through florist shops. The types of plants include cut flowers, cut foliage, indoor houseplants such as tropical flowering or foliage plants, and special occasion flowering potted plants such as azaleas and poinsettias.

Florists' crops are prone to numerous diseases caused by fungi, oomycetes, bacteria, nematodes, viruses, viroids, phytoplasmas, and abiotic agents (Horst 2001). Since consumers prefer and typically require high quality aesthetics for florists' crops, any marring due to foliar pathogens will greatly reduce crop value if not render a crop nonsalable. Stem and root pathogens can reduce crop growth or cause wilting or plant death. Continued grower livelihood requires successful management of pathogens using all available components of integrated disease management (scouting, record keeping, disease/pathogen identification, prevention, sanitation, plant culture, biological and chemical tools) and applying them effectively based on understanding pathogen biology, genetics, host-interactions, and life cycles.

Over the last 100 years or so, understanding of common pathogens has increased substantially and has laid the foundation for studying newly arising pathogens. While much of the research in the beginning of the twentieth century focused on developing basic biological and epidemiological knowledge for fungal and bacterial plant pathogens, professors and graduate students also began more in depth investigations into methods and tools to mitigate diseases; some of the first graduate student stipends provided came from grower donations for nursery stock and tree diseases (Whetzel 1945).

Discovery of tools to manage disease-causing organisms prior to the twentieth century occurred often by happenstance. For example, the discovery of Bordeaux mixture as a fungicide came about by grape farmers applying the liquid to vines to

discourage thieves from taking ripened grapes. Sprayed vines had less downy mildew (Gianessi and Reigner 2005; Morton and Staub 2008). Early disease management tools tended to be inorganic molecules such as elemental sulfur dust and copper sulfate and were applied primarily to high value food crops (Russell 2005) rather than florists' crops or row crops grown over large acreages. From the beginning of the twentieth century through World War II, major changes occurred for managing plant diseases and pests. Growers shifted from mixing their own concoctions to purchasing products manufactured by companies (registrants) who registered the materials with the US government (Davis 2014). Over time, the focus on fungicides and bactericides for specialty food crops shifted with row crop agriculture driving the discovery and development of new active ingredients since the mid-twentieth century. A notable exception was the active ingredient dodemorph that was commercialized and introduced in 1965 specifically for controlling rose powdery mildew (Russell 2005).

The sections below cover contemporary processes and perspectives for discovering new active ingredients, developing them into viable products, and registering them within the United States. Since plant pathology and the tools to manage florists' crop diseases continually evolve, references to historical perspectives are included to show changing viewpoints over time.

2 Discovery, Development, and Registration

2.1 Active Ingredient Discovery and Early Development

Discovery of new active ingredients whether chemical, biological, or genetic focuses on screening prospective tools for their activity against certain key model pathogens. Ideas for prospective tools arise from many different areas. For example, new chemicals can arise from studying biopesticide-pathogen interactions or other microbial interspecies interactions and isolating the molecule(s) associated with pathogen inhibition or mortality (Erjavec et al. 2012). The strobilurin class of fungicides arose from this strategy with the subsequent design of molecules that possessed a similar structure to the original molecule but with slightly different properties (Balba 2007; Bartlett et al. 2002). Chemicals may also be discovered by understanding key biological processes within the pathogen that are distinct from pathways in mammals or plants and designing molecules that interfere with that process. It is estimated that more than 150,000 synthesized molecules are screened for a single new registered active ingredient (Phillips McDougall 2016). New biologically based active ingredients are discovered in similar ways to new chemicals. These discoveries can be based on verbal histories or lore or on keen observations of natural situations. New biopesticides are also revealed by isolating and identifying endophytes from plants and soils that inhibit pathogen growth in lab studies.

Once a new active ingredient is discovered, a key step before continuing on the development pathway is determining whether it can economically be manufactured. For a new biological active ingredient, it might involve developing a suitable large-scale

fermentation process. For microbial or plant extracts, this might be whether the organism can be grown quickly, efficiently, and still consistently produce a quality extract containing the active moiety. For chemistry, this could involve determining whether synthesis of the molecule can be scaled up economically.

At the same time as determining production methodologies, a new active ingredient will be screened on a broader array of pathogens to learn the breadth and limitations of its effectiveness. These studies initially occur in the laboratory, then in the greenhouse, and subsequently in small plots in the field with well-studied pathogen-host systems.

These early stages of development may be accompanied by a battery of studies to examine stability and degradation of the active ingredient under different conditions (moisture, light, temperature) and its degradation pathways (photolysis, hydrolysis, microbial, plant metabolism, mammalian metabolism, secondary metabolites, etc.). Further characterization of its target site and mode of action occur as well as deposition and movement within plant tissues. In the United States, chemically based active ingredients tend to have broader requirements for toxicology and ecotoxicology studies than biopesticides (US EPA 2016c).

In addition to characterizing an active ingredient's physicochemical characteristics, beginning steps occur to create a formulation to deliver it appropriately, at the very least for the small plot field tests. Further refinements occur through late stage development. Considerations may include buffering at a certain pH to maintain optimal stability, including the best balance of surfactants to keep the active solubilized or in solution so it does not precipitate out, and delivering a formulation that is easy to use and does not have negative characteristics like the propensity to clog sprayer nozzles in the case of liquid products or like undue amounts of dust as granular based products are dispensed and applied.

Early development is also the period when initial acute toxicology studies are conducted for mammalian oral, inhalation, and dermal toxicity. If there are any concerns raised during early development, additional research activities for that active ingredient are dropped and it is no longer considered a viable candidate.

2.2 Product Development: Efficacy and Crop Safety

When an active ingredient passes early screening, large scale field trials commence examining performance under different climatic conditions and weather patterns. Researchers collect data on a wider range of pathogens and crops. Most of these research activities occur on food and fiber crops. However, during the late stages of product development when the registrant is confident of commercialization, research activities are expanded to include environmental horticulture crops and their diseases.

In studying the efficacy of a new product for a specific pathogen, a series of different rates (rate range) is used to find the optimal concentration using different application methodologies. For active ingredients with limited plant mobility, foliar applications will typically be screened for foliar and floral diseases only.

Applications for trunk or stem diseases may also include painting. For materials with plant systemic activity, soil applications may be screened in addition to foliar to determine efficacy level and length of residual activity. The length of residual control is assessed by stopping applications and then continuing to rate efficacy until it is clear the treatment is no longer effective. Experiments are established to screen for preventative activity (what happens when it is applied prior to being challenged with a pathogen) or curative activity (what happens when it is applied as the pathogen is first causing infection or soon after).

In addition to examining a product by itself, it may be screened as part of a programmatic approach. It will be tested in rotation or as a tank mix with other active ingredients. This will determine whether the actives together provide the same, enhanced, or diminished activity. Tank mix compatibility may be included in the product label.

Products are also screened for whether they impact plant growth and development. The triazole fungicides, for example, are known to have growth regulator effects on certain crops. Assessing growth habit, chlorosis, necrosis, flower bud abortion, floral color and number, or other unusual occurrences after application on multiple crops contributes to how registrants write product labels.

Continued screening of new late-stage development active ingredients and currently registered products ensures that end users have the most up-to-date information regarding options for managing diseases.

2.3 Product Development: Toxicology

Simultaneously to large scale field testing, in depth toxicology and ecotoxicology studies begin. Acute testing occurs for the active ingredient formulated as a manufacturing use product (only used to make end use formulations) and as proposed end use formulations. These studies are designed to determine the concentration at which 50% of the tested population will have a negative reaction after a single exposure. The "six pack" is acute oral toxicity, acute dermal toxicity, acute inhalation toxicity, primary eye irritation, primary dermal irritation, and dermal sensitization (US EPA 2016b). The results from these six studies will classify the formulated product label into caution, warning, or danger signal words. Information on acute neurotoxicity is required, and delayed neurotoxicity data may be required.

Subchronic testing examines concentrations below those found during the acute testing to screen for impacts with repeated ingestion or contact with the active ingredient. These studies include 90 day oral, 21/28 or 90 day dermal, and 90 day neurotoxicity (US EPA 2016c). Depending on the outcomes of the acute studies, 90 day inhalation and 28 day delayed neurotoxicity may be required. Chronic testing includes long-term feeding studies to examine lethality and carcinogenicity. Developmental toxicity, reproduction/fertility, and mutagenicity testing are required to examine potential sublethal impacts. Mammalian metabolism and immunotoxicity studies further characterize active ingredients for how they break down and are excreted and whether they impact the immune system. Toxicity to birds, fish, aquatic

invertebrates, and honey bees is examined as is phytotoxicity for terrestrial and aquatic plants.

Worker safety is paramount. It is required to determine whether applicators will be exposed to the product during application and whether workers who come in contact with the plants after application will be exposed. The types of studies include dermal and inhalation exposure, dislodgeable foliar residues, soil residue dissipation, and how the product will be used. For example, if the product will be formulated as a time-release aerosol which can be set to release after the applicator leaves the greenhouse range, the applicator will have little exposure.

In addition to the degradation studies listed above in Sect. 2.1, additional environmental fate studies are conducted to determine the likelihood an active ingredient will move out of the treated area and/or persist. These include leaching through and adsorption/desorption in soil, terrestrial dissipation studies, and monitoring ground water if an active ingredient and/or its metabolites may be likely to leach into ground water. For example, a highly water soluble active ingredient with little capacity to bond to organic matter in the soil might require ground water monitoring.

Please note that the above are highlights of US EPA toxicology and ecotoxicology studies, and anyone considering registering a new biological or chemical active ingredient should consult with the US EPA or other relevant national agency for full requirements and tiered assessment guidelines.

2.4 Product Registration in the United States

Registration of products in the United States today is very different from what is was at the turn of the twentieth century. Up through the early 1900s, products were sold based on the reputation of the manufacturer or were created by the end user from recipes without any federal or state system to vet and register them. Toxicology as a scientific discipline was in its infancy and focused solely on acute mortality rather than potentially subtle chronic impacts (Davis 2014). The primary factors for a successful product at that time were whether it was efficacious and whether the level of plant injury was acceptable, and these were solely determined by the marketplace.

Throughout the twentieth century, toxicology and risk assessment developed and expanded to address not only acute and chronic human concerns but also impacts on the environment. Since initial experiments into the toxicology of DDT during the 1930s and 1940s which focused almost exclusively on acute human mortality, toxicology and assessing risk from the use of tools to manage pests, diseases and weeds has evolved (Davis 2014) to include environmental and product chemistry; avian, aquatic, and mammalian toxicology; endocrine disruption; and other nontarget impacts as described previously. In the United States, these studies must be conducted under Good Laboratory Practices (GLP) and are reviewed by the US EPA and collaborating regulatory bodies such as California Department of Pesticide Regulation and international agencies when products are considered for joint review

Table 1 Increasing cost to discover, develop, and register new chemical tools (1980–2014)

Year	Cost of discovery and development (US$ M)	2014 value (US$ M)	Expenditure increase (US$ M)
1980	$23	$66	$220
1995	$152	$236	$50
2000	$184	$253	$33
2008	$256	$281	$5
2014	$286	$286	–

(Phillips McDougall 2016); http://www.usinflationcalculator.com/

and registration by multiple countries at the same time. Under joint review, the regulatory bodies divide the submitted registration package for simultaneous, collaborative evaluation. US EPA carefully considers the hazards and risks based on the submitted data package (US EPA 2016a). If US EPA finds the active ingredient and its formulated product(s) meet a predetermined level of concern, it approves the registration. If the product does not meet the level of concern, US EPA will recommend mitigation language be added to the product label (such as additional protective gear for applicators or a longer re-entry interval) or fewer uses for the final label (such as only greenhouse and not outdoor applications) prior to approving the registration.

From 1980 to 2014, the cost to discover, develop, and register a single new chemical crop protection tool increased from US $23 million to US $286 million (Phillips McDougall 2016). This is amortized across all the molecules screened. When converting this to US dollar value in 2014, expenditures for a single active ingredient have increased to US $220 million since the 1980s (Table 1), an indication of the enhanced testing requirements globally to ensure product safety and performance with the heightened awareness of potential subacute, chronic impacts of these tools on nontarget organisms.

3 Practical Considerations

Once a product is registered and commercialized, growers may revise disease control programs to include the new active ingredient. The characteristics of the new product will determine how best it can be incorporated. A product that has curative activity (can stop disease progression) can be combined with scouting for application as soon as disease symptoms are observed. A product with preventive activity (must be present prior to the pathogen) will be applied when environmental conditions are suitable for disease development without obvious plant symptoms. Reading the product label, technical literature from registrants and research bulletins from extension personnel will provide guidance on use. This section covers some practical considerations on product labels, application technology, and resistance management.

3.1 Labels and Use Directions

Based on all the research activities over a 10–12 year span, registrants write product labels. These labels contain vital information to maintain worker safety (applicators and handlers), safeguard consumers (preharvest intervals for any edible crops on the label and re-entry intervals for anyone touching the plants without protective gear), prevent unintended impacts on the environment, and provide optimal efficacy (US EPA 2016b). The label does have many parts with the worker safety and environmental considerations at the beginning. The use directions focus on how to apply the product. Rotational or tank mix recommendations may be included, but of particular note are the maximum number of applications prior to rotating to a different mode of action. The FRAC code is prominently displayed on most fungicide labels to aid growers in selecting tools of different modes of action.

Application methods can include foliar sprays, soil drench, sprench (a heavy foliar spray with the intent to apply product to the soil also), soil injection, and other potential methods such as irrigation line injection, ebb and flow benches, dip application, or painting. Routine calibration of equipment and checking delivery are critical for ensuring the intended amount of product is being applied. Calibration of the applicator is just as important. An applicator spraying foliage who moves slower will potentially deliver more active ingredient per area than an applicator with a faster pace, assuming the same volume output from the application equipment (Wilen 2011; Anon 2016).

3.2 Application Technology

Application equipment is designed based on the product formulation and targeted plant part (foliage, trunk/stem, roots). Products may be formulated as liquids (soluble concentrates, flowable/suspension concentrates, emulsifiable concentrates, microemulsions, oil dispersions, microencapsulated particles) or as solids (wettable powders, water dispersible granulars, granulars). Additional formulation types and the international coding system were published by CropLife International (Anon. 2008). With the exception of granulars, aerosols, and other ready-to-use preparations, formulations are designed to be diluted with water and applied using sprayers, liquid fertilizer lines, and soil or tree injection equipment. Aerosols typically are self-contained application equipment that may deliver the active ingredient in a carrier other than water.

3.2.1 Sprayers

There are various types of sprayers available but they fall into three groups: high volume hydraulic sprayer, targeted low-volume sprayers, and ultra-low volume sprayers.

High volume sprayers deliver volumes up to and beyond 1870 L per hectare (200 gal per acre), typically delivering large droplets, but droplet size can vary considerably with nozzles and pressure (70–200 μm). Hydraulic sprayers build

pressure through a mechanical or hand-operated pump and can range from low to high pressure. Nozzles create different droplet sizes and spray patterns. Most product labels are written based on volume levels needed to achieve good coverage with high volume sprayers. Plugs and young plants may need 93–234 L per hectare (10–25 gal per acre), while larger plants in production might need up to 1870 L per hectare (200 gal per acre). Mature shrubs and trees in the landscape may require 3741 L per hectare (400 gal per acre) or more for adequate coverage, but it is exceedingly rare for an entire hectare (or acre) to be planted with trees and shrubs requiring simultaneous treatment for pathogen management. While high volume sprayers can be mechanized and be used to treat large areas, some can be used for smaller areas or spot sprays.

Targeted low-volume sprayers deliver the same active ingredient load per area but in higher concentrations with smaller droplets and less volume. These sprayers may deliver 47–421 L per hectare (5–45 gal per acre). With appropriate nozzles hydraulic sprayers can be used. Electrostatic sprayers fit into this category. Electrostatic sprayers apply a charge to the solution that improves coverage by causing the spray droplets and plants to attract each other. The droplet size for electrostatic sprayers is between 15 and 25 μm.

Ultra-low volume sprayers deliver product in very little water. The droplet size is typically 50–60 μm. Foggers, coldfoggers, and aerosols fit in this category.

3.2.2 Granular Applicators

There are two common types of granular product spreaders: rotary and drop. The rotary spreader has a spinning disk (manual or mechanical) which distributes granules to the front and sides. In the drop spreader, granules drop through open holes in the bottom of the hopper. These types of spreaders tend to be used for outdoor applications for plants grown in the field. For indoor applications, granular products may be incorporated into the soil mix prior to planting, or, for certain spot applications, granulars may be applied using a shaker can.

3.3 Resistance Management

The Fungicide Resistance Action Committee (FRAC) classifies chemically and biologically active ingredients by mode of action (www.frac.info). Each mode of action group member has the same site of activity and is assigned a FRAC code which appears prominently on the US label. If a pathogen population develops resistance to one member, all members of that group will not be as effective on the same population. To delay development of resistance, it is recommended that applicators rotate to different modes of action. Labels for most products containing active ingredients with single site modes of action require rotation to a different FRAC group after two or three consecutive applications. Tank mixing two or more active ingredients from different FRAC groups is another strategy to preserve effective control over time. Knowing which actives are effective for different fungal stages leads to combinations that can interfere with multiple stages such as

preventing cell membrane formation (FRAC 3) combined with reduced mitochondrial respiration (FRAC 11). Often registrants will offer premix formulations containing two actives which target different sites. Even then, most labels will require rotation to other FRAC groups after multiple consecutive applications of single site mode of action materials.

4 Products Currently Registered in the United States

Products in the marketplace continually shift as new tools are discovered and older products discontinued. The complement of choices may vary depending on marketplace and prevalence of disease. In the United States during 2016, 22 different mode of action classes are registered for managing pathogens on environmental horticulture plants. These products are classified by the types of pathogens they manage. For example, fungicides manage fungi (ascomycetes, basidiomycetes) and water molds (oomycetes) and bactericides manage bacteria. However, some tools, particularly broad spectrum active ingredients with general biocide activity, may manage diseases across pathogen types.

4.1 Fungicides

Fungi and oomycetes constitute the largest number of plant pathogens that cause more than 85% of plant diseases and are responsible for most diseases of environmental horticulture plants. They damage plants by killing cells and/or causing plant stress. They are typically multicellular organisms that produce tiny thread-like filaments called hyphae. Most pathogenic fungi produce spores which serve to reproduce and disseminate them. Management of diseases caused by fungi and oomycetes commonly requires use of fungicides that are discussed below.

4.1.1 Inorganics

Sulfur was the first fungicide known (Williams and Cooper 2004; Horsfall 1956) and was the earliest fungicide registered in the United States for application to florists' crops (Table 2). It is still used today by commercial growers and homeowners.

Sulfur belongs to a group of contact fungicides that are considered protectants or preventive fungicides. They remain on the plant surface and do not penetrate into the plant. They inhibit the fungi on the plant surface, usually spore germination, so the fungus will not be able to infect the plant. Contact fungicides affect multiple sites in fungi so resistance to these is not a major concern. They are used with resistance-prone systemic active ingredients as a part of fungicide resistance programs if multiple applications of fungicides are needed for season long disease control.

Copper-based compounds. See information under Sect. 4.2.

Bicarbonates – Several potassium bicarbonate products have been registered to control powdery mildew and other fungal diseases of environmental horticulture

Table 2 Active ingredients currently registered in the United States for managing diseases of environmental horticulture crops[a]

Active ingredient[b]	Product trade name(s)[c]	Product type[d]	Year of first US registration for environmental horticulture crops[e]	FRAC code[f]	MOA code	Chemical group
Ametoctradin + dimethomorph	Orvego	Designed chemical	2012	45 + 40	C8: QoI + F5: CAA fungicides	Triazolo-pyrimidylamine + cinnamic acid amide
Azoxystrobin	Heritage	Designed chemical	1998	11	C3: QoI	Methoxy-acrylates
Azoxystrobin + benzovindiflupyr	Mural	Designed chemical	2015	11 + 7	C3: QoI +	Methoxy-acrylates +
Azoxystrobin + difenoconazole	Alibi Flora	Designed chemical	2015[i]	11 + 3	C3: QoI + G1: DMI (SBI class 1)	Methoxy-acrylates + triazole
Bacillus amyloliquifaciens Strain D747 (aka B. subtilis CX-9032)	Double Nickel, Triathlon BA	Microbial	2011	44	F6: Microbial	Microbial disrupters of pathogen cell membranes
Bacillus subtilis strain QST 713	Cease, Rhapsody, Serenade Optimum, etc.	Microbial	2014	44	F6: Microbial	Microbial disrupters of pathogen cell membranes
Bacillus subtilis var *amyloliquefaciens* strain FZB24	Taegro	Microbial	2000	44	F6: Microbial	Microbial disrupters of pathogen cell membranes

(*continued*)

Table 2 (continued)

Active ingredient[b]	Product trade name(s)[c]	Product type[d]	Year of first US registration for environmental horticulture crops[e]	FRAC code[f]	MOA code	Chemical group
Bacillus subtilis strain IAB/BSO3	Mildore	Microbial	2015	44	F6: Microbial	Microbial disrupters of pathogen cell membranes
Bacillus subtilis GB03	Companion	Microbial	2008	44	F6: Microbial	Microbial disrupters of pathogen cell membranes
Captan	Captan	Designed chemical	1973	M4	Multi-site: phthalimide	Phthalimide
Chlorothalonil	Concorde, Daconil, Echo, etc.	Designed chemical	1974 (conifers) 1985	M5	Multi-site: chloronitrile (phthalonitrile)	Chloronitrile (phthalonitrile)
Chlorothalonil + zinc	Daconil Zn	Designed + Natural Chemical	1992 (conifers) 1997	M5	Multi-site: chloronitrile (phthalonitrile) +	Chloronitrile (phthalonitrile) +
Cinnamaldehyde	Cinnacure	Natural chemical	1999	NC		
Coniothyrium minitans	Contans	Microbial	2002			
Copper diammonia diacetate complets	Copper-Count-N	Natural chemical	1997	M1	Multi-site	Inorganic
Copper hydroxide	Champ, Champion, CuPRO, Kentan, Kocide, etc.	Natural c-hemical	1983	M1	Multi-site	Inorganic

Copper hydroxide + copper oxychloride	Badge SC, Badge *X2*	Natural chemical	2005	M1	Multi-site	Inorganic
Copper octanoate	Camelot O	Natural chemical	1997	M1	Multi-site	Inorganic
Copper sulfate	Basicop, Cuprofix	Natural chemical	1975[g]	M1	Multi-site	Inorganic
Copper sulfate pentahydrate	Phyton	Natural chemical	1991	M1	Multi-site	Inorganic
Cuprous oxide	Nordox	Natural chemical	2000	M1	Multi-site	Inorganic
Cyazofamid	Segway O	Designed chemical	2007	21	C4: QiI	Methoxy-acrylate
Cyprodinil + fludioxonil	Palladium	Designed chemical	2010	9 + 12	D1: AP fungicides + E2: PP fungicides	Aniline-pyrimidine + phenylpyrrole
Dicloran	Botran	Designed chemical	1997	14	F3: AH fungicides	Aromatic hydrocarbons
Didecyl dimethyl ammonium chloride	Kleengrow	Natural chemical	2007	NC		
Dimethomorph	Stature	Designed chemical	2002	40	F5: CAA fungicides	Cinnamic acid amimde
Etridiazole	Terrazole, Truban	Designed chemical	1972	14	F3: AH fungicides	1,2,4 thiadizole
Extract of *Reynoutria sachalinensis*	Regalia	Plant extract	2000	P5	P5: plant extract	Complex mixture, ethanol extract
Fenamidone	Fenstop	Designed chemical	2004	11	C3: QoI	Imidazolinone
Fenarimol	Rubigan	Designed Chemical	1990[g]	3	G1: DMI (SBI class 1)	Pyrimidine
Fenhexamid	Decree	Designed chemical	1999	17	G3: hydroxyanilide (SBI class III)	Hydroxyanilide
Fludioxonil	Medallion	Designed chemical	1997	12	E2: PP fungicides	Phenylpyrrole

(*continued*)

Table 2 (continued)

Active ingredient[b]	Product trade name(s)[c]	Product type[d]	Year of first US registration for environmental horticulture crops[e]	FRAC code[f]	MOA code	Chemical group
Fluopicolide	Adorn	Designed chemical	2008	43	B5: benzamide	Pyridinylmethyl-benzamide
Fluoxastrobin	Disarm, Fame	Designed chemical	2007	11	C3 QoI	Dihydro-dioxazine
Flutolanil	Contrast, Prostar	Designed chemical	1999	7	C2: SDHI	Phenyl-benzamide
Fosetyl Al	Aliette	Designed chemical	1983	33	Unknown: phosphonate	Ethyl phosphonate
Gliocladum catelunatum strain J446	Prestop	Microbial	2006	NC		
Gliocladium virens GL21	SoilGard	Microbial	1990	NC		
Hydrogen dioxide	ZeroTol	Natural chemical	1998[i]	NC		
Hydrogen dioxide + peroxyacetic acid	ZeroTol 2.0	Natural chemical	2014	NC		
Iprodione	Chipco 26019, etc.	Designed chemical	1986	2	E3: dicarboximide	Dicarboximide
Mancozeb	Dithane, Fore Protect, Pentathlon, etc.	Designed chemical	1965[g]	M3	Multi-site: dithiocarbamates	Dithiocarbamates and relatives
Mandipropamid	Micora	Designed chemical	2011	40	F5: CAA fungicides	Mandelic acid amide
Mefenoxam (metalaxyl-M)	Subdue, Fenox	Designed chemical	1996	4	A1 Phenyl amide	Acyl alanine
Metconazole	Tourney	Designed chemical	2007	3	G1: DMI (SBI class I)	Triazole

Mineral oil	JMS Stylet Oil, SuffOil-X, etc.	Natural chemical	1992	NC		
Myclobutanil	Eagle, etc.	Designed chemical	2003	3	G1: DMI (SBI class I)	Triazole
Hydrophobic neem oil extract	Triact 70, Trilogy, etc.	Plant extract	1997	18B		
Oxathiapiprolin	Segovis	Designed chemical	2015	U15		
Paraffinic oil	Sunspray UltraFine oil, Ultra Pure Oil, etc.	Natural chemical	1989	NC		
PCNB	Terraclor	Designed chemical	1971[h]	14		
Phosphorus acid salts	Agrifos, Alude, Fosphite, Magellan, OxiPhos, Phos Fungicide, Rampart, Vital, etc.	Natural chemical	2002	33	Unknown: phosphonate *(literature indicates induced resistance and direct toxicity)*	Phosphonate
Piperalin	Pipron	Designed chemical	1972	5	G2: amines (morpholines) SBI Class 2	Piperidine
Polyoxin D zinc salt	Affirm, Veranda	Microbial extract	2005	19	H4: Polyoxins	Polyoxins
Potassium bicarbonate	Armicarb, Kaligreen, Milstop	Natural chemical	1997	NC		
Potassium salts of fatty acids	M-Pede, Ringer Aphid Mite Attack, Safer Soap, etc.	Natural chemical	1980	NC		

(*continued*)

Table 2 (continued)

Active ingredient[b]	Product trade name(s)[c]	Product type[d]	Year of first US registration for environmental horticulture crops[e]	FRAC code[f]	MOA code	Chemical group
Potassium silicate	Sil-Matrix, Carbom Defense	Natural chemical	2006	NC		
Propamocarb	Banol, Proplant	Designed chemical	1987	28	F4: carbamates	Carbamates
Propiconazole	Banner Maxx, ProPensity	Designed chemical	1995 (elm, oak) 2005	3	G1: DMI (SBI class I)	Imidazole
Pyraclostrobin	Insignia, Empress Intrinsic	Designed chemical	2006	11	C3: QoI	Methoxy-carbamate
Pyraclostrobin + boscalid	Pageant Intrinsic	Designed chemical	2008	11 + 7	C3: QoI + C2: SDHI	Methoxy-carbamate + pyridine-carboxamide
Pyraclostrobin + fluxapyroxad	Orkestra Intrinsic	Designed chemical	2016	11 + 7	C3: QoI + C2: SDHI	Methoxy-carbamate + pyrazole-carboxamide
Streptomyces griseoviridis K61	Mycostop	Microbial	1993	NC		
Streptomyces lydicus	Actinovate	Microbial	2004	NC		
Streptomycin sulfate	Agrimycin, Firewall	Microbial extract	1961	25	D4: glucopyranosyl antibiotic	Glucopyranosyl antibiotic

Sulfur	Microthiol Disperss, Bonide Micronized Sulfur, Miller's Garden Sulphur, etc.	Natural chemical	1966[g] (1948 was listed on EPA for first label, but 1966 was earliest scanned posted label)	M2	Multi-site	Inorganic
Tebuconazole	Torque, Tebuconazole SC T&O Fungicide	Designed chemical	2002	3	G1: DMI (SBI class I)	Triazole
Thiophanate methyl	3336, OHP 6672, etc.	Designed chemical	1983	1	B1: MBC	Thiophanate
Triadimefon	Bayleton, Strike	Designed chemical	1990	3	G1: DMI (SBI class I)	Triazole
Trichoderma asperelloides strain JM41R	Tricho Plus Biofungicide	Microbial	2015	NC		
Trichoderma hamatum strain 382	Incept	Microbial	2010	NC		
Trichoderma harzianum	PlantShield, RootShield	Microbial	1995	NC		
Trichoderma harzianum + Trichoderma virens	RootShield Plus	Microbial	2012	NC		
Trifloxystrobin	Compass O	Designed chemical	1999	11	C3: QoI	Oximino-acetate
Triflumizole	Terraguard	Designed chemical	1991	3	G1: DMI (SBI class I)	Imidazole

(*continued*)

Table 2 (continued)

Active ingredient[b]	Product trade name(s)[c]	Product type[d]	Year of first US registration for environmental horticulture crops[e]	FRAC code[f]	MOA code	Chemical group
Triticonazole	Trinity	Designed chemical	2013	3	G1: DMI (SBI class I)	Triazole
Ziram	Ziram	Designed chemical	1981[g]	M3	Multi-site: dithiocarbamates and relatives	Dithiocarbamates and relatives

[a]Published with kind permission of © Cristi Palmer and Ely Vea, 2016. All Rights Reserved
[b]Mixtures of two or more active ingredients are only listed if one of the active ingredients is not available in the United States as a stand-alone product
[c]Trade names are listed for products registered in the United States for use on environmental horticulture crops as of 2016. While this information is included to aid end users, the names may shift over time and multiple formulations may exist. Additional trade names may be available
[d]These categories represent generalized groupings of active ingredients. Natural chemical refers to those active ingredients existing in nature which can be formulated into products with minimal human intervention. Designed chemical refers to active ingredients discovered to be active through high-throughput screening or chemically transformed natural molecules. The latter are known as biologics in the pharmaceutical industry and are represented by the strobilurin class of chemistry in agriculture
[e]This is the first year the active ingredient was registered with US Environmental Protection Agency for environmental horticulture uses. The active ingredient may have been registered for edible crop or other uses in prior years
[f]These are the mode of action group codes assigned by the Fungicide Resistance Action Committee. Full descriptions and listings can be found at www.frac.info
[g]Earliest year legible label available with environmental horticulture uses at the US EPA Pesticide Product Label System (http://ofmpub.epa.gov/apex/pesticides/f?p=PPLS:1)
[h]No longer registered
[i]Currently registered but not available commercially

plants. They mainly inhibit fungal mycelial development. Its mode of action is linked with osmotic pressure, pH, and specific bicarbonate/carbonate ion effects. Like sulfur, the bicarbonates belong to a group of contact fungicides that are considered protectants or preventive fungicides.

Phosphonic acid and derivatives – This broad category of phosphonate fungicides includes several products that are registered to control mainly oomycete diseases including seedling blights, damping-off, root rots, foliar blights, and downy mildews.

Phosphonate fungicides have systemic activity and application methods including foliar spray, soil drench, soil incorporation, basal bark application, bare root dip, etc. They are recommended for application prior to disease development for optimum control. Their mode of action has not been established, but both a direct effect by inhibiting the oxidative phosphorylation or other metabolic processes in the fungi and an indirect effect by stimulating the plant's natural defense response against pathogen attack have been suggested. Risk for phosphonate resistance is considered lower than single-site activity fungicides.

Silicon – Silicon-based fungicides like potassium silicate are used for preventative control of fungal diseases of environmental horticulture plants. Silicon belongs to a group of contact fungicides that are considered protectants or preventive fungicides. Silica accumulation in cell walls is believed to act as a physical barrier to pathogen infection resulting in plant disease resistance.

4.1.2 Dithiocarbamates

The dithiocarbamates (thiram, zineb, maneb, mancozeb, etc.), first introduced in 1942 with thiram, are the most widely used group of organic fungicides. This group represented a major improvement over the previously used inorganic fungicides in that they were more active, less phytotoxic, and easier to prepare by the user. Of these active ingredients, the most widely used is mancozeb, a broad spectrum protectant fungicide which was first registered on environmental horticulture plants in 1965. The dithiocarbamates are considered contact, multi-site activity fungicides, inhibiting -SH groups in amino acids, proteins, and enzymes. Thus, the risk for resistance is lower than single-site activity fungicides.

4.1.3 Substituted Aromatics

This group of preventative contact fungicides includes three active ingredients that are registered on environmental horticulture plants. Chlorothalonil is one of the most widely used broad spectrum fungicide in turf and ornamentals. The other two, etridiazole and pentachloronitrobenzene or PCNB, control mainly soil-borne diseases caused by several pathogens that include *Phytophthora, Pythium, Rhizoctonia*, etc. These fungicides are considered multi-site activity fungicides, inhibiting amino acids, proteins, and enzymes by combining with amino and thiol groups. Thus, the risk for resistance is considered lower than single-site activity fungicides.

4.1.4 Pthalimides

This group of fungicides (captan, captafol, folpet) was introduced for plant disease control in the 1950s and early 1960s. Captan is currently registered for use on environmental horticulture plants. The pthalimides are considered contact, multi-site activity fungicides, inhibiting a host of processes in the cell, including enzyme function, amino acid synthesis, cellular metabolism, etc. Thus, the risk for resistance is considered lower than single-site activity fungicides.

4.1.5 Benzimidazoles

This group of fungicides was introduced for plant disease control in the 1960s and early 1970s. This group includes benomyl, carbendazim, thiabendazole, thiophanate-methyl, etc. Thiophanate-methyl is currently registered on environmental horticulture plants. The benzimidazoles are contact fungicides that possess unique properties not seen before in the protectant fungicides. These included low use rates, broad spectrum, and systemicity with post-infection action that allowed for extended spray interval. They interfere with fungal mitosis (normal cell division), so they affect the growth of fungi. They affect fungi at a very specific site in the metabolic pathway, inhibiting DNA synthesis (nuclear division) and, therefore, resistance to these fungicides develops very easily. See recommendations for resistance management from product labels and Sect. 3.3 for managing fungicide resistance.

4.1.6 Sterol Inhibitors

Sterol inhibitors, other than the triazoles (see Sect. 4.1.8), include hydroxyanilides (fenhexamid, etc.), imidazoles (imazalil, prochloraz, triflumizole, etc.), morpholines (tridemorph, etc.), piperazine (triforine), piperidines (piperalin, etc.), pyrimidines (fenarimol, etc.), and others. Products in these groups that are registered on florists' crops include fenhexamid, imazalil, triflumizole, triforine, piperalin, and fenarimol.

4.1.7 Dicarboximides

This is a group of agricultural fungicides, including iprodione, procymidone, and vinclozolin, that have excellent protectant activity on diseases caused by *Botrytis, Monilinia,* and *Sclerotinia.* Iprodione is registered on florists' crops. Dicarboximides inhibit DNA and RNA synthesis, cell division, and cellular metabolism. Resistance to dicarboximides has been well documented in several crops; hence, recommendations for avoiding fungicide resistance should be practiced. See recommendations for resistance management from product labels and Sect. 3.3 for managing fungicide resistance.

4.1.8 Triazoles

Triazoles are the largest class of fungicides. They are highly effective against many different fungal diseases, especially powdery mildews, rusts, and many leaf-spotting fungi. Triadimefon was the first triazole to be registered on florists' crops in 1990.

Since then, other triazoles were labeled including metconazole, myclobutanil, propiconazole, tebuconazole, and triticonazole.

The triazoles belong to a group of demethylation inhibitors (DMI) that inhibit one specific enzyme, C14-demethylase, which plays a role in sterol production. Sterols, such as ergosterol, are needed for membrane structure and function, making them essential for the development of functional cell walls. Therefore, these fungicides result in abnormal fungal growth and eventually death. They are locally systemically mobile in plant tissues, readily taken up by leaves and moves within the leaf. Triazoles may be applied preventively or as early-infection treatments. They affect fungi at a very specific site in the metabolic pathway; hence, resistance to these fungicides develops very easily. Therefore, recommendations for avoiding fungicide resistance should be practiced. These include avoiding repeated use, rotation with products with a different mode of action, preventative application, and applying rates within the labelled range.

4.1.9 Phenylamides

The phenylamide fungicides, including metalaxyl, mefenoxam (metalaxyl-M), benalaxyl, and kiralaxyl, brought a completely new level of control to the Oomycetes through their systemic properties by offering protection to the plants as seed treatments and soil or foliar applications. Mefenoxam is registered for use on florist' crops. The phenylamides are specific inhibitors of ribosomal RNA polymerases in the target fungi. Resistance to phenylamides develops very easily and has been well documented in several crops; hence, recommendations for avoiding fungicide resistance should be practiced. See recommendations for resistance management from product labels and Sect. 3.3 for managing fungicide resistance.

4.1.10 Strobilurins

The strobilurin fungicides, commonly referred to as Q_oI fungicides, have a broad spectrum of activity, are highly efficacious, and are suitable for a wide range of crops. The first active ingredient azoxystrobin was registered on florists' crops in 1998. Since then, additional Q_oI fungicides have been developed, with several now commercially available or expected to be available soon. These include fenamidone, fluoxastrobin, pyraclostrobin, and trifloxystrobin. In addition, several products contain strobilurins formulated with other fungicides to broaden the activity spectrum and slow down development of resistance. These products include azoxystrobin + benzovindiflupyr, azoxystrobin + difenoconazole, pyraclostrobin + boscalid, and pyraclostrobin + fluxapyroxad.

The strobilurin fungicides exhibit translaminar movement, and thus the fungicide can be found on both leaf surfaces even if only one leaf surface was treated. Some active ingredients in this group, e.g., azoxystrobin, also move systemically in the plant's vascular system. They kill germinating spores, and thus they are excellent as preventive fungicides. Although some products in this group provide curative activity, the best use of Q_oI fungicides is to apply them before infection takes

place. All Q_oI fungicides share a common biochemical mode of action: they all interfere with energy production in the fungal cell by blocking electron transfer at the site of quinol oxidation (the Qo site) in the cytochrome bc_1 complex, preventing ATP formation. They affect fungi at a very specific site in the metabolic pathway and, therefore, resistance to these fungicides develops very easily. See recommendations for resistance management from product labels and Sect. 3.3 for managing fungicide resistance.

4.1.11 Biofungicides

Biological fungicides (biofungicides) are composed of beneficial microorganisms, including specialized bacteria (*Bacillus, Pseudomonas*, and *Streptomyces*, etc.) and fungi (*Gliocladium* and *Trichoderma*, etc.) that suppress soilborne and foliar plant pathogens. Many of these microorganisms are found naturally occurring in soils. Researchers have isolated specific strains which have been formulated with additives to enhance their performance and storage. There are a number of ways in which biofungicides work, including direct competition or exclusion; antibiosis, predation, or parasitism; induced resistance; and plant growth promotion. Thus, the risk for resistance is considered lower than chemical fungicides.

Products containing biological control agents that are currently registered for disease management of florists' crops include *Bacillus subtilis*, *Coniothyrium minitans*, *Gliocladum catelunatum*, *Gliocladum virens*, *Streptomyces griseoviridis*, *Streptomyces lydicus*, *Trichoderma asperelloides*, *Trichoderma hamatum*, *Trichoderma harzianum*, and *Trichoderma harzianum* + *Trichoderma virens*. These are environmentally friendly integrated pest management (IPM) tools with great potential, but, currently, they do not adequately control ornamental plant diseases on their own in most cases.

4.2 Bactericides

Bacteria are single cell microscopic organisms. Bacteria are ubiquitous in and around plants. Only a small portion are plant pathogenic, but they can be difficult to manage. Several groups of products used to manage bacterial diseases of florists' crops are discussed below.

4.2.1 Inorganics

Copper-based compounds – There are several different copper-based fungicides registered for use in environmental horticulture plants. They have broad-spectrum activity, acting on bacteria as well as fungi. These products include copper diammonia diacetate complex, copper hydroxide, copper hydroxide + copper oxychloride, copper octanoate, copper sulfate, copper sulfate pentahydrate, and cuprous oxide. They are considered contact, multi-site activity bactericides/fungicides, with activity resulting from

nonspecific denaturation of proteins and enzymes. Thus, the risk for resistance is considered lower than single-site activity fungicides.

4.2.2 Antibiotics

Streptomycin – Streptomycin belongs to a group of bactericidal antibiotics including kasugamycin, oxytetracycline, and terramycin used in agriculture. Streptomycin was discovered and developed in the 1940s to be the first effective treatment for tuberculosis. Products based on streptomycin sulfate were registered in 1961 to control bacterial and fungal diseases of florists' crops. They are used as preventive treatments and can be applied as foliar and blossom spray, soil drench, pre-plant dip, etc. Streptomycin interferes with amino acid synthesis. Resistance to streptomycin sulfate has developed in some agricultural crops, and hence recommendations for avoiding fungicide resistance should be practiced. See recommendations for resistance management from product labels and Sect. 3.3 for managing antibiotic resistance.

4.2.3 Biocides

Several active ingredients with general biocide activity are registered for bacterial control either as disinfectants of tools and hard surfaces or as applications on plants for preventative and early curative control. These include quaternary ammonium compounds like didecyl dimethyl ammonium chloride (KleenGrow) and oxidizing agents like hydrogen dioxide + hydrogen peroxide (ZeroTol 2.0) and hydrogen peroxide + peroxyacetic acid (SaniDate 12.0).

4.3 Nematicides

Nematodes are small, multicellular wormlike animals. Depending on the type, they feed on roots, bulbs, stems, leaves, or seeds. The majority of plant parasitic nematodes live in the soil and damage plants by feeding in large numbers on the roots, impairing the plant's ability to take up water and nutrients. Although nematodes rarely kill plants, they can drastically reduce plant growth and quality (Table 3).

Management of nematode diseases is primarily preventative. Using healthy nursery stock is the best way to avoid soilborne nematode diseases. Most nematicides used to control soil nematodes are very toxic and can only be applied by certified applicators. Soil fumigants recommended for use in florists' crops before planting include 1,3-dichloropropene and sodium methyldithiocarbamate. These cannot be used in greenhouses or other enclosed areas. These fumigants are generally recommended only as a last resort when other management strategies have not been successful or are not available. Ethoprop is registered as a soil treatment for field nursery stock only. One biological nematicide, *Myrothecium verrucaria*, is registered as a soil treatment for florists' crops. For foliar nematodes, products are not readily available.

Table 3 Activity, use sites, and re-entry interval of active ingredients registered in the United States for environmental horticulture crops during 2016[a]

Active ingredient	Product trade names in the United States[b]	FRAC code[c]	Registered use sites in the United States (2016)[d]	REI	Bacteria	Botrytis	Downy mildew	Leaf spots anthracnose	Nonoomycete root rots	Phytophthora	Powdery mildew	Pythium	Rusts
Ametoctradin + dimethomorph	Orvego	45 + 40	G, I, L, N, S	12 h			X			X			
Azoxystrobin	Heritage	11	G, L, N, S	4 h		X	X	X	X	X	X	X	X
Azoxystrobin + benzovindiflupyr	Mural	11 + 7	G, L, N, S	12 h		X	X	X	X	X	X	X	X
Azoxystrobin + difenoconazole	Alibi Flora	11 + 3	G, L, N, S	12 h		X		X			X		X
Bacillus subtilis	Cease, Companion, DPZ, Rhapsody, Serenade Optimum, etc.	44	G, I, N, S	4 h	X	X	X	X	X	X	X	X	X
Captan	Captan	M4	G	48 h		X		X	X	X		X	
Chlorothalonil	Concorde, Daconil, Echo, etc.	M5	G, L, N, S	12 h		X		X		X	X		X
Chlorothalonil + propiconazole	Concert II	M5 + 3	N	12 h		X		X			X		X
Chlorothalonil + thiophanate methyl	Consyst, Spectro	M5 + 1	G, I, N	12 h		X		X	X		X		X
Chlorothalonil + zinc	Daconil Zn	M5	N	12 h		X		X		X	X		X
Cinnamaldehyde	Cinnacure	NC	G, N	4 h							X		
Copper ammonium complex	Copper Count-N, etc.	M1	G, I, N, S	12 h	X	X		X			X		
Copper hydroxide	Champ, Champion, CuPRO, Kentan, Kocide, etc.	M1	G, I, N, S	48 h	X	X	X	X		X	X		

Copper hydroxide + copper oxychloride	Badge SC, Badge *X2*	M1	G, N, S	48 h	X	X		X		X	X		
Copper hydroxide + mancozeb	Junction	M1 + M3	G, N	48 h	X	X	X	X			X		X
Copper octanoate	Camelot O	M1	G, I, N, S	4 h	X	X		X			X		X
Copper sulfate	Basicop, Cuprofix	M1	G, N, S	48 h	X	X		X			X		
Copper sulfate pentahydrate	Phyton	M1	G, I, N	24 h	X	X	X	X			X		X
Cuprous oxide	Nordox	M1	G, I, N, S	24 h		X		X			X		
Cyazofamid	Segway O	21	G, N	12 h			X			X		X	
Cyprodinil + fludioxonil	Palladium	9 + 12	G, L, N, S	12 h		X		X	X		X		
Dicloran	Botran	14	G, N	12 h		X		X					
Didecyl dimethyl ammonium chloride	Kleengrow	NC	G	48 h	X	X	X	X	X	X	X	X	
Dimethomorph	Stature SC	40	G, L, N	12 h			X			X			
EBDC	Fore, Pentathlon, etc.	M3	G, N	24 h						X			
Etridiazole	Terrazole, Truban	14	G, N	12 h					X	X		X	
Etridiazole + thiophanate methyl	Banrot	14 + 1	G	12 h					X	X		X	
Extract of *Reynoutria sachalinensis*	Regalia	P5	G, I, L, N, S	4 h	X	X	X	X			X		
Fenamidone	Fenstop	11	G	12 h			X			X		X	
Fenarimol	Rubigan	3	G, N	12 h							X		
Fenhexamid	Decree	17	G, N	12 h		X		X					
Fludioxonil	Medallion	12	G, I, L, N, S	12 h		X		X	X				

(*continued*)

Table 3 (continued)

Active ingredient	Product trade names in the United States[b]	FRAC code[c]	Registered use sites in the United States (2016)[d]	REI	Bacteria	Botrytis	Downy mildew	Leaf spots anthracnose	Nonoomycete root rots	Phytophthora	Powdery mildew	Pythium	Rusts
Fludioxonil + mefenoxam	Hurricane[e]	12 + 4	G, I, N, S	48 h					X	X		X	
Fluopicolide	Adorn	43	G, L, N, S	12 h			X			X		X	
Fluoxastrobin	Disarm, Fame	11	G, I, N, S	12 h		X	X	X	X	X	X		X
Flutolanil	Contrast, Prostar	7	G, N, S	12 h					X				X
Fosetyl Al	Aliette	33	G, N	12 h	X		X			X		X	
Gliocladum catelunatum strain J446	Prestop	NC	G, I, N, S	0 h		X		X	X	X		X	
Gliocladium virens	SoilGard	NC	G, I, N	0 h					X	X		X	
Hydrogen dioxide	ZeroTol	NC	G, I, N	0 h	X	X		X		X	X	X	
Iprodione	Chipco 26019, etc.	2	G, N	12 h		X		X	X				
Iprodione + thiophanate methyl	26/36	2 + 1	G, N	12 h		X		X	X				
Mancozeb	Dithane, Protect, Pentathlon, etc.	M3	G, N	24 h	X	X	X	X		X		X	X
Mancozeb + myclobutanil	Clevis[e]	M3 + 3	G, N	24 h		X		X			X		X
Mancozeb + thiophanate methyl	Zyban	M3 + 1	G, N	24 h		X		X			X		X

Mandipropamid	Micora	40	G, L, N, S	4 h			X			X			
Mefenoxam	Subdue, Fenox	4	G, L, N, S	0 h or 48 h			X			X		X	
Metconazole	Tourney	3	N	0 h or 12 h		X		X	X		X		X
Mineral oil	JMS Stylet Oil, SuffOil-X, etc.	NC	G, N	4 h		X		X			X		X
Myclobutanil	Eagle, etc.	3	G, N	24 h				X			X		X
Neem oil extract	Triact 70, Trilogy, etc.	18B	G, I, L, N, S	4 h		X	X	X			X		X
Oxathiapiprolin	Segovis	U15	G, L, N, S	4 h			X			X			
PCNB	Terraclor	14	G, I, N, S	12 h					X				
Phosphorus acid salts	Alude, Fosphite, Magellan, Rampart, Vital, etc.	33	G, N	4 h	X		X			X	X	X	
Piperalin	Pipron	5	G	12 h							X		
Polyoxin D zinc salt	Affirm, Veranda	19	G, L, N, S	4 h		X	X	X	X		X		
Potassium bicarbonate	Milstop	NC	G, I, L, N, S	1 h		X		X			X		X
Potassium salts of fatty acids	M-Pede	NC	G	12 h							X		
Potassium silicate	Sil-Matrix	NC	G, N	4 h							X		
Propamocarb	Banol, Proplant	28	G, N	24 h						X		X	
Propiconazole	Banner Maxx, ProPensity	3	N	12 h		X		X			X		X

(*continued*)

Table 3 (continued)

Active ingredient	Product trade names in the United States[b]	FRAC code[c]	Registered use sites in the United States (2016)[d]	REI	Bacteria	Botrytis	Downy mildew	Leaf spots anthracnose	Nonoomycete root rots	Phytophthora	Powdery mildew	Pythium	Rusts
Pyraclostrobin	Insignia, Empress Intrinsic	11	G, I, L, N, S	12 h		X	X	X	X	X	X	X	X
Pyraclostrobin + boscalid	Pageant Intrinsic	11 + 7	G, I, L, N, S	12 h		X	X	X	X	X	X	X	X
Pyraclostrobin + fluxapyroxad	Orkestra Intrinsic	11 + 7	G, I, L, N, S	12 h		X	X	X	X	X	X	X	X
Streptomyces griseoviridis	Mycostop	NC	G, N	4 h		X		X	X	X		X	
Streptomyces lydicus	Actinovate	NC	G, I, L, N, S	1 h	X	X	X	X	X	X	X	X	
Streptomycin sulfate	Agrimycin, Firewall	25	N	12 h	X								
Sulfur	Microthiol Dispersss, etc.	M2	G, N	24 h		X		X			X		X
Tebuconazole	Torque, Tebuconazole SC T&O Fungicide	3	N	12 h		X		X			X		X
Thiophanate methyl	3336, OHP 6672, etc.	1	G, I, L, N, S	12 h		X		X	X		X		X

Triadimefon	Bayleton, Strike	3	G, N	12 h		X		X			X		X
Trichoderma harzianum	PlantShield, RootShield	NC	G, I, N, S	0 h					X	X	X	X	
Trichoderma harzianum + *Trichoderma virens*	RootShield Plus	NC	G, I, N, S	0 h or 4 h					X	X		X	
Trifloxystrobin	Compass O	11	G, I, L, N, S	12 h		X	X	X	X	X	X		X
Trifloxystrobin + triadimefon	Strike Plus	11 + 3	G, N	12 h		X	X	X			X		X
Triflumizole	Terraguard	3	G, I, N, S	12 h		X		X	X		X		X
Triticonazole	Trinity	3	G, I, L, N, S	12 h		X		X	X		X		
Ziram	Ziram	M3	G, N	48 h		X		X			X		

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[b]Trade names are listed for products registered in the United States for use on environmental horticulture crops as of 2016. While this information is included to aid end users, the names may shift over time and multiple formulations may exist. Additional trade names may be available

[c]These are the mode of action group codes assigned by the Fungicide Resistance Action Committee. Full descriptions and listings can be found at www.frac.info

[d]Registered Use Sites: *G* greenhouse, *L* lath house, *I* indoors/interiorscape, *N* nursery, *R* landscape, *S* shade house

[e]Currently registered but not available commercially

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