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Integrated Pest Management for Greenhouse Fruits and Vegetables

Ministry of Agriculture, Food and Agribusiness

Ontario

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Front Cover
Top left: Aphid colony in greenhouse peppers being attacked by the biological control agent, Aphidius colemani, resulting in mummified aphids.
Top right: Botrytis grey mould infecting the stem of a pepper plant
Bottom left: Powdery mildew infecting fruits of strawberries.
Bottom right: Whiteflies on a tomato leaf.

Back Cover: Looper larva feeding on a pepper leaf.

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Publication 836 | Book A
Integrated Pest Management for Greenhouse Fruits and Vegetables

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Pub 836: *Growing Greenhouse Vegetables in Ontario*, 2010 (Archived)
Screening of greenhouses for insect exclusion
Sanitation guidelines for management of pests and diseases of greenhouse vegetables

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OVERVIEW

This publication is Part A of a series that will replace Publication 836: *Growing Greenhouse Vegetables*. Visit ontario.ca/crops for more information.

This publication provides an overview of integrated pest management (IPM) for greenhouse fruit and vegetable production in Ontario. Concepts useful for a comprehensive understanding of pests and their management will be discussed. This information is meant to be used as a guide for those working directly with or within IPM programs.

For timely updates and information about the Greenhouse Vegetable Course refer to ONGreenhouseVegetables.ca.

Publications to follow in this series will provide crop specific IPM information for greenhouse tomatoes, peppers, eggplant, cucumbers, lettuce and strawberries. These publications will include more details on specific crop pests and their management. As controlled environment agriculture[19] has evolved substantially over the last decade, careful consideration needs to be given towards the impact of production practices, like supplemental lighting, on pest and beneficial populations in the growing environment.

Greenhouse IPM is not a one-size-fits-all program. Each greenhouse is unique. The combination of the structure, crop and growing techniques creates different environments. Considering each greenhouse as its own ecosystem is necessary to understand the specific needs of the crop as they change throughout the growing season and from year to year.

The protection within a greenhouse provides opportunities. The structure limits the impacts of external factors like rain and wind. It also allows for specific techniques like biological control to be applied in a relatively controlled approach to minimize establishment of pests and reduce the spread within.

Growers and IPM professionals can interact with the crop and the greenhouse environment through careful and regular inspections and respond with appropriate techniques to maximize plant health. Success of these interactions can be improved by deepening the knowledge and understanding of how these ecosystems are developed and how they change over time.

The information provided in this publication can be used to begin building a foundation of knowledge for entry level positions or enhance knowledge gained by experienced employees that may not have a background in IPM. In either case, this tool is meant to support decision-making and is best used when combined with a strong network of like-minded and knowledgeable individuals. Have a team of IPM professionals, including scientists and industry. Ask questions. Share ideas and experiences. Try and try again until something works for you.

CHAPTER 1

Crop Pests

A crop pest is an unwanted, destructive organism that has a negative impact on production. Crop pests include organisms such as **arthropods, plant pathogens** or weeds. In greenhouse fruit and vegetable production in Ontario, arthropods and plant pathogens are the primary pest types.

A wide range of management strategies can be deployed by producers and will depend on the pest type or species within that type. Therefore, making informed decisions begins with a good understanding of the organisms encountered in production systems.

Names of Arthropods and Pathogens

All species of living organisms, including arthropods and pathogens, are typically identified by distinct two-part names (scientific or Latin) consisting of their **genus** and species. Many species also have recognized common names, but these do not always exist and sometimes cause confusion when users apply the same common name for identifying multiple different species. For example, the moth species *Ostrinia nubilalis* is often referred to as the European corn borer but is also known as the European corn worm or the European high-flyer. These common names are confusing because in addition to there being multiple common names, this species is not technically a worm and it feeds on more than just corn. Similarly, there are many different host-specific pathogen species that cause a disease we collectively call powdery mildew.

Using scientific names generally allows for clearer communication universally. It is also worth noting that scientific names do change as new approaches to **taxonomy** based on **genetic sequencing** often re-classifies organisms when more information is known.

Arthropod Pests

Arthropods

Arthropods (Phylum: Arthropoda) are the largest phylum in the animal kingdom. A distinguishing physical feature of an arthropod is the presence of an **exoskeleton**, which is an external jointed skeleton with a **cuticle** made of **chitin** (a complex sugar). The hardened exoskeleton limits growth until **moulting**, a process in which a rapidly growing arthropod produces a new, larger cuticle to replace one that is too small, which is then shed. The body is segmented, with paired, jointed appendages. Arthropods usually have **compound eyes** as their primary source of vision and **ocelli** (also called simple eyes) which are most often used to detect the direction of light, or a combination of these.

Two classes of arthropods are economically important pests in crop production: insects (Class: Insecta) and mites (Class: Arachnida; Subclass: Acari). Insects and mites can also be beneficial and used in biological control (biocontrol) programs. The ability to distinguish between insects and mites can have important implications for pest management decision-making.

Insects

Insect External Anatomy

Insects have three body segments: head, **thorax** and abdomen. Figure 1 shows examples of the external anatomy of three adults from different orders of insects:

- moths (Order: Lepidoptera)
- beetles (Order: Coleoptera)
- true bugs (Order: Hemiptera)

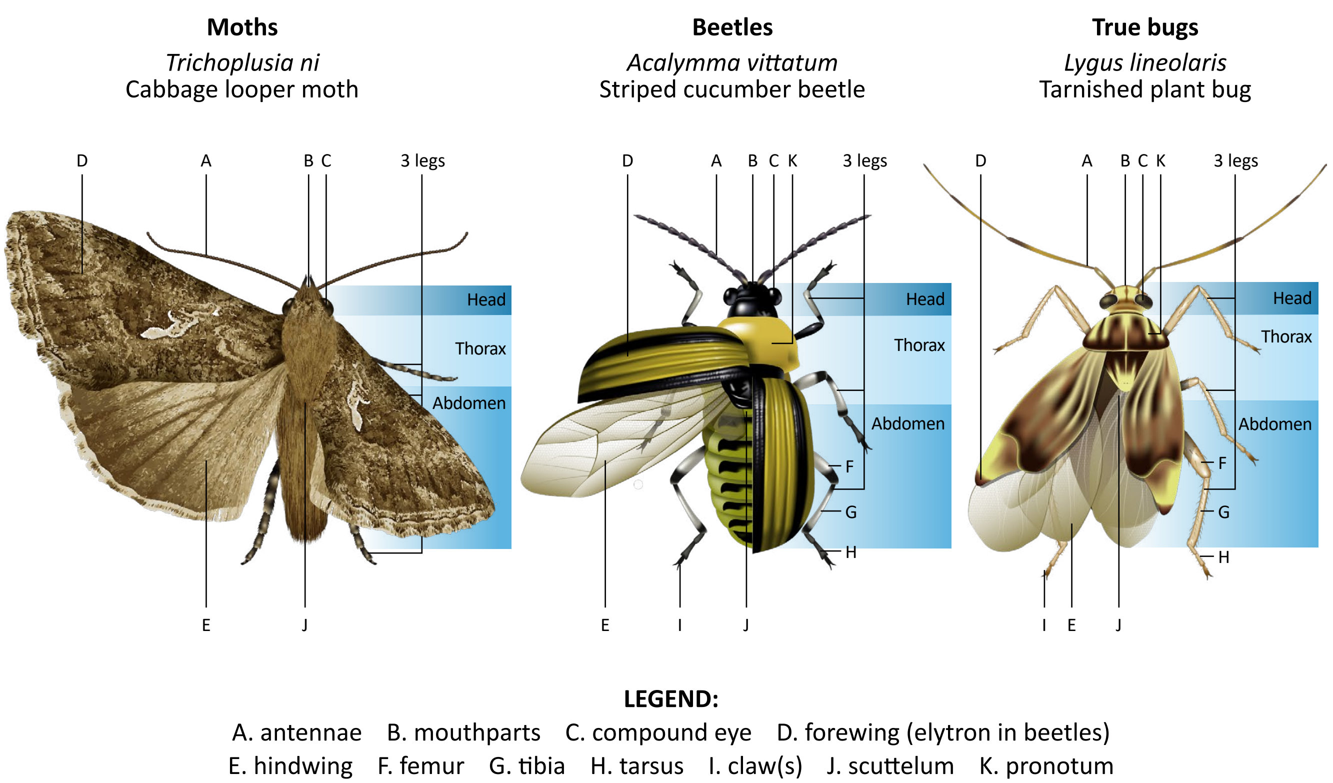

Figure 1. Insect external anatomy. Moths (Lepidoptera: *Trichoplusia ni*, cabbage looper moth); Beetles (Coleoptera: *Acalymma vittatum*, striped cucumber beetle); True bugs (Hemiptera: *Lygus lineolaris,* tarnished plant bug), left to right.

The head includes mouthparts, eyes and a pair of **antennae**. In adult insects, the thorax includes three pairs of jointed legs (six total) and one or two pairs of wings. Immature insects lack wings and antennae and may have other structures used for mobility, such as **prolegs** in caterpillars. The abdomen includes the digestive, excretory and reproductive organs. Insects breathe through **spiracles** in their exoskeleton.

Although most insect species have wings in the adult stage, some species do not or only produce winged adults under certain conditions. For example, aphids produce winged adults only when the **colony** is overcrowded and they need to disperse to uninhabited plants.

It is common to group insects together based on their mouthparts to give insight into their feeding habits and damage patterns. There are four main types of insect mouthparts:

- chewing (used by caterpillars and beetles)
- piercing-sucking (used by true bugs and thrips)
- siphoning (used by adult Lepidoptera; butterflies, moths, skippers)
- lapping (used by adult flies)

Most crop pests of concern have either chewing or piercing-sucking mouthparts.

Chewing mouthparts are used by leaf-feeding insects such as beetles and caterpillars to consume plant tissue (Figure 2A).

Mandibles vary in shape and size. They are used to cut and crush food but are sometimes used for defence. The **maxillae** contain segmented **maxillary palps** and may assist in food processing. Crop damage caused by insects with chewing mouthparts includes:

- holes in leaves **(defoliation)**, stems, buds, flowers or fruit
- leaf tissue eaten between veins except for the upper or lower **epidermis (window-paning)**
- scars or scraped plant tissue
- discoloured plant tissue
- missing/severed leaves, stems, buds or roots

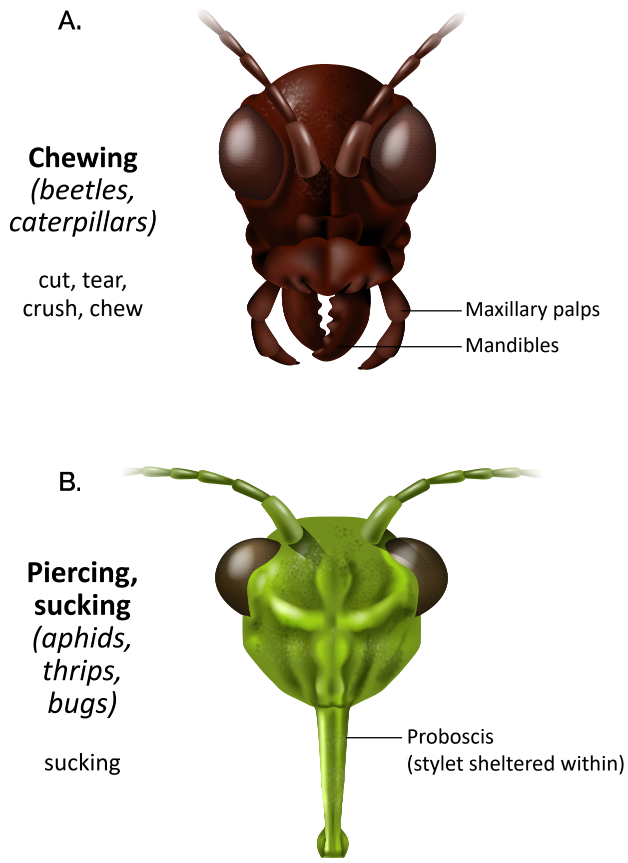

Figure 2. Insect mouthparts. (A) Chewing mouthparts. (B) Piercing-sucking mouthparts.

Piercing-sucking insects, like thrips, aphids and whiteflies, use a needle-like **stylet** to pierce tissue of its host plant (Figure 2B). Shape, size and number of stylets varies between insect orders and species. True bugs have long, thin paired stylets that form a stylet-bundle. Thrips have asymmetrical rasping-sucking mouthparts. The mandible on the right is reduced or **vestigial**, while the mandible on the left is modified as a stylet to rasp (scrape) away the plant's epidermis. Two paired maxillary stylets are modified as a tube-like structure for piercing and sucking. Crop damage caused by insects with piercing-sucking mouthparts includes:

- silvering or speckling of plant tissue
- deformed plant tissue/distorted growth
- yellowing of plant tissue **(chlorosis)**
- stunting
- wilting

Some beneficial insects also use chewing or piercing-sucking mouthparts to consume their arthropod hosts.

Insect Biology

Insects undergo major physical changes when they develop from egg to adult. Immature insects (**larvae** or **nymphs**) must shed their exoskeletons (moult) to grow. Each immature stage is called an **instar**. The number of instars depends on the species and environmental conditions. There are two types of insect life cycles or **metamorphoses**: complete or incomplete.

Complete metamorphosis is when an insect transitions through four distinct phases (Figure 3):

1. egg
2. larvae
3. pupa
4. adult

During complete metamorphosis, adults lay eggs, which hatch into immature stages called larvae. Larvae do not resemble adults and may rely on completely different food sources. Larvae moult through several instars before pupating. During the non-feeding **pupal** stage, larval tissues reorganize into adult insects.

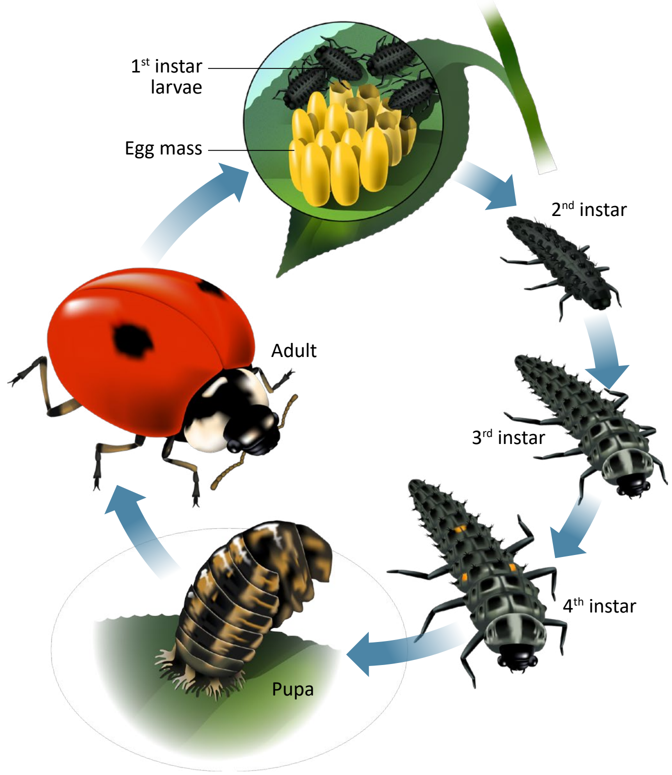

Figure 3. Complete metamorphosis showing the life cycle of *Adalia bipunctata*, two-spotted lady beetle.

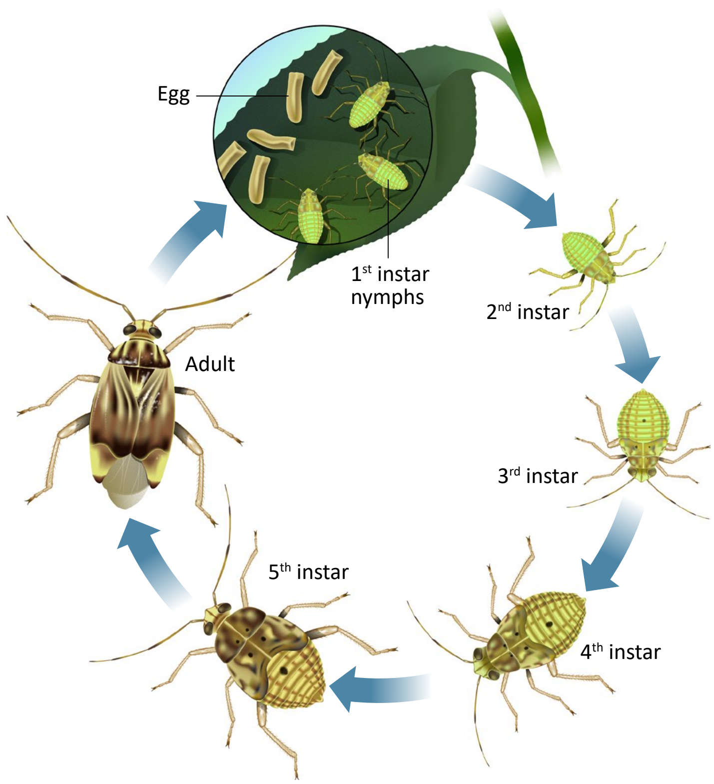

Figure 4. Incomplete metamorphosis showing the life cycle of *Lygus lineolaris*, tarnished plant bug.

Incomplete metamorphosis occurs when an insect transitions through three phases (Figure 4):

1. egg
2. nymph
3. adult

In this instance, the immature stages called nymphs, closely resemble the adults but are smaller and lack some adult features, such as wings. Nymphs moult through several instars and during the late instar stages, external wing buds form.

Exceptions to these life cycles exist such as in species that reproduce asexually under certain environmental conditions. For example, many aphids reproduce asexually by cloning **(parthenogenesis)**, for most of the year. In this case all adults are female (sometimes called mothers) and give birth to live female nymphs (sometimes called daughters) rather than laying eggs. Under late-summer outdoor conditions, both male and female offspring are produced and once mated, the aphids will overwinter as eggs. However, it is uncommon to find aphids laying eggs in protected greenhouses.

Mites

Mite External Anatomy

Mites are small, sometimes microscopic and have two body segments (**gnathosoma** and **idiosoma**). Figure 5 shows the external anatomy of two different orders of mites:[79]

- a plant feeder (Order: Trombidiformes)
- a predator (Order: Mesostigmata)

The gnathosoma or mouthparts include structures used for feeding, such as **chelicerae** and **palps**.

Chelicerae are specialized, pincer-like feeding appendages that are sometimes modified into piercing stylets as seen in the two-spotted spider mite, *Tetranychus urticae*.

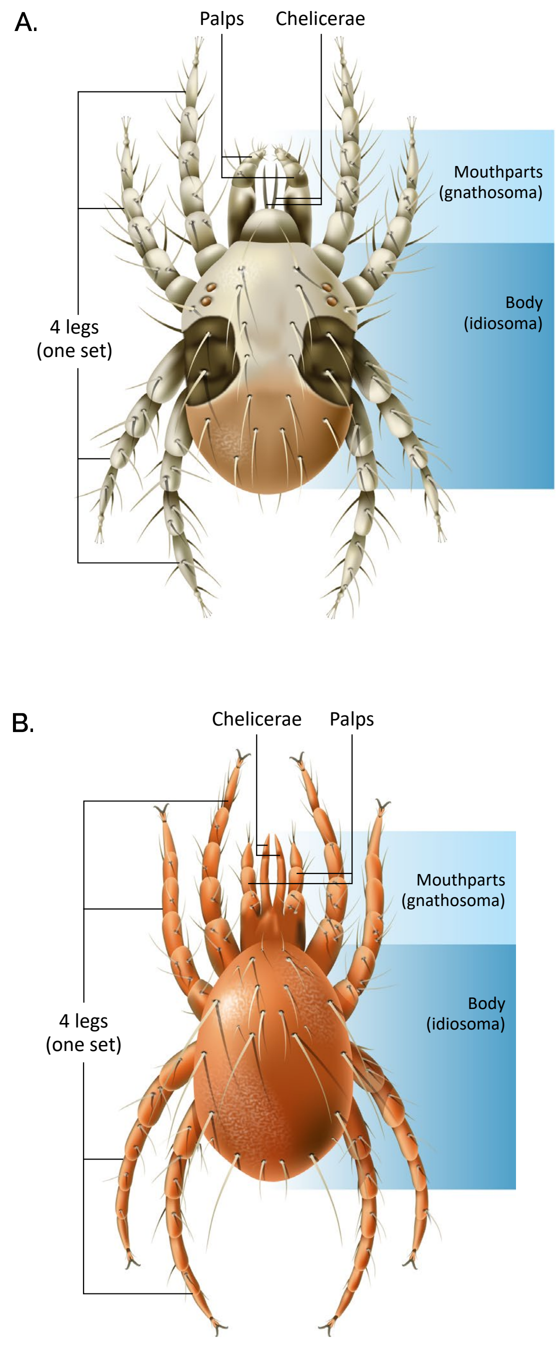

Figure 5. Mite external anatomy.
(A) Trombidiformes: the plant feeder, two-spotted spider mite, *Tetranychus urticae.* (B) Mesostigmata: the predator, *Phytoseiulus persimilis.*

Palps or pedipalps are segmented and may be simple sensory organs or predatory organs that will grasp or pierce. Feeding injury caused by mites includes:

- yellow **stippling** (cell contents of the leaf have been removed), browning/bronzing or mottling of the leaves
- leaf drop
- flower abortion
- bronzed, cracked fruit
- wilting
- distorted, thickened and twisted growth

In adult mites, the idiosoma or body usually includes four pairs of legs (eight total). Some immature mites have three pairs of legs (6 total) until they mature. Another exception includes members of the Eriotophydae family, such as tomato russet mites, *Aculops lycopersici,* which only have two pairs of legs (four total). Unlike insects, all mites lack wings and antennae. Mites breathe through **stigmata** (respiratory pores on the body) and have various presentations of sclerotized shields (hardened cuticle offering protection). Depending on the species, they may have no eyes or a few pairs. For example, two-spotted spider mites have two pairs of eyes, while their predators, *Phytoseiulus persimilis*, have none, but instead use plant **volatiles** to locate prey.

Mite Biology

Mites also undergo physical changes when they develop from egg to adult. Mite developmental stages include the egg, larva, nymph and adult (Figure 6). Like incomplete metamorphosis in insects, immature mites (larvae and nymphs) strongly resemble the adults and must shed their exoskeletons (moult) to grow. There may be several nymphal stages (such as protonymph, deutonymph and tritonymph), depending on the species.

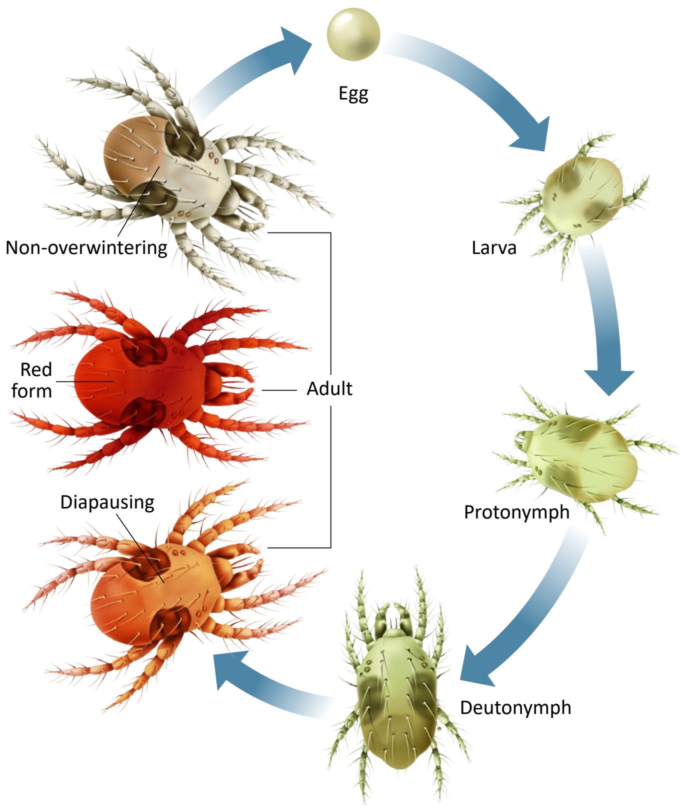

Figure 6. Life cycle of two-spotted spider mite.

Factors Influencing Growth and Development of Arthropods

The growth and development of arthropods is largely **temperature-dependent** but can also be influenced by other factors such as humidity, availability of food and genetic traits. Optimum environments differ between species. Generally, the warmer the temperature, the more rapid the development. All species have minimum and maximum temperature thresholds in which development can occur, although they may still survive outside of those thresholds. Beyond these thresholds are lower and upper temperatures that will cause mortality. The exact temperature can vary by species but a minimum developmental threshold of 10°C is common for many arthropods. Below this temperature, the individual may stop developing but may not die unless directly exposed to more extreme low temperatures such as well below -4°C. During production, temperatures will be above 10˚C for most crops. However, during fall or winter clean out between crops, temperatures indoors are often between 0˚C–5˚C, unless the greenhouse is heated. In this case, any residual arthropods may be inactive and become active once a new crop is in place and the heat is turned on. Similarly, 32˚C is a common maximum threshold, where an individual's development levels off or it stops developing entirely. Mortality may occur with exposures between 35˚C–40˚C for many species. In a production setting, consider these impacts on both arthropod pests and beneficials. Additional measures may need to be taken during extreme heat events as those experienced in southern parts of Ontario.

Additionally, some arthropods enter a physiological resting stage called **diapause** that is triggered by adverse environmental conditions including seasonal changes like winter. Triggers include daylength, temperature and food quality. During diapause there is no feeding, reproduction or much movement. Some species enter diapause as eggs, immatures or adults.

Arthropods within a controlled environment with artificial lights can still be triggered to enter diapause. An example of a diapausing pest is the two-spotted spider mite, which is known to reproduce and feed less in winter. Beneficial arthropods such as *Orius insidiosus*, can also enter diapause. In this case, adults will still feed and reproduce, but offspring produced in the greenhouse will not become reproductively active. Since thrips populations can persist in greenhouse environments throughout the winter, management of this pest can be more difficult where there are limitations for use of a key predator such as *O. insidiosus*. Diapause of insects can sometimes create a disequilibrium between predator and prey population dynamics.

Common Arthropod Pests of Greenhouse Fruits and Vegetables

Appendix A provides a list of common arthropod pests of greenhouse fruits and vegetables in Ontario.

Plant Pathogens

Plant diseases are caused by a pathogen (the **causal agent**) that interrupts or modifies the plant's vital functions. This typically leads to a decrease in crop productivity or quality. The disease may alter the plant's normal structure, growth, function or other activities.

In greenhouse and indoor food crop production, pathogens include:

- **fungi**
- **oomycetes**
- **bacteria**
- **viruses**
- **viroids**

Pathogenic nematodes can also cause plant disease, although their occurrence is uncommon in modern greenhouse food production in Ontario. All plant tissues, including roots, crowns, stems, shoots, leaves, flowers, fruit, vascular tissues and seeds, can be infected by pathogens. Certain fungi, bacteria, viruses and nematodes can also be beneficial. Some of these have been commercialized and are used in biocontrol programs.

Understanding **signs** and **symptoms** of plant pathogens and diseases is important for initial identification of a problem and assists with diagnosis. Signs are the visible presence of the pathogen or by-product such as spores, fruiting bodies or bacterial ooze. Symptoms are the visible effects of disease as plants react internally and externally to the pathogen such as wilting or mottling of leaves.

Fungi

Fungi are **eukaryotic** (their genetic material is contained in a nucleus), multi-celled organisms. Unlike plants, they lack chlorophyll (and thus the capacity for photosynthesis) and contain chitin in their cell walls. As they lack the capacity to produce sugars from photosynthesis, most species rely on plants (living or dead biomass) as a carbon source.

Macroscopic fungi form large fruiting bodies and some edible species are cultivated as food crops. Microscopic fungi are often referred to as mildews or moulds. Fungi are ubiquitous in the environment. They break down organic matter and release carbon, oxygen, nitrogen and phosphorus into the soil and atmosphere. Microscopic fungi are the most frequent causal agents of plant disease in temperate climates.

Depending on species, fungal pathogens can infect all plant parts and incite a wide range of symptoms including:

- root rot
- wilt
- crown or stem lesions
- chlorosis
- death of plant tissue **(necrosis)**

Some species form conspicuous masses of **mycelia** and/or fruiting bodies on plant surfaces.

Biology of Fungi

Fungal life cycles vary greatly depending on species, host plant and environmental conditions required to cause infections in plants. Fungi can undergo both asexual and sexual reproduction.

Generally, fungal life cycle stages include:

- mycelia (vegetative structures)
- **conidia** (asexual spores)
- **ascospores, basidiospores, zygospores** (sexual spores)

Fungal mycelium is a mat of **hyphae** (long, thin vegetative fungal structures). Asexual spores (conidia) are frequently responsible for the initiation of secondary **disease cycles** (in the case of fungi causing polycyclic disease, where the pathogen completes more than one generation during a crop cycle and spreads to uninfected areas or plants). Spores resulting from sexual reproduction (for example ascospores) may be contained in fruiting bodies and initiate primary cycles of infection. Some fruiting bodies are better equipped for survival over long periods of time. Such as the overwintering structures, **chasmothecia**.

Figure 7 illustrates the disease cycle of powdery mildew on a strawberry crop. Strawberry powdery mildew, *Podosphaera aphanis* (previously known as *Sphaerotheca macularis* f. sp. *fragariae*) can infect strawberry leaves, fruit, stolons and flowers.[21],[52] It needs a living host to complete its life cycle and reproduce. It can overwinter in plant tissue as fruiting bodies (chasmothecia). Chasmothecia release ascospores.

Ascospores are carried by wind or on surfaces and infection occurs when they contact strawberry plant tissue under the right conditions and germinate. Germinating spores develop germ tubes that grow into hyphae produced in conspicuous networks called mycelia. During asexual reproduction, conidial chains (asexual fruiting bodies) form from the mycelium and release spores called conidia. These conidia will spread and germinate on host tissue under the right conditions and continue the disease cycle.

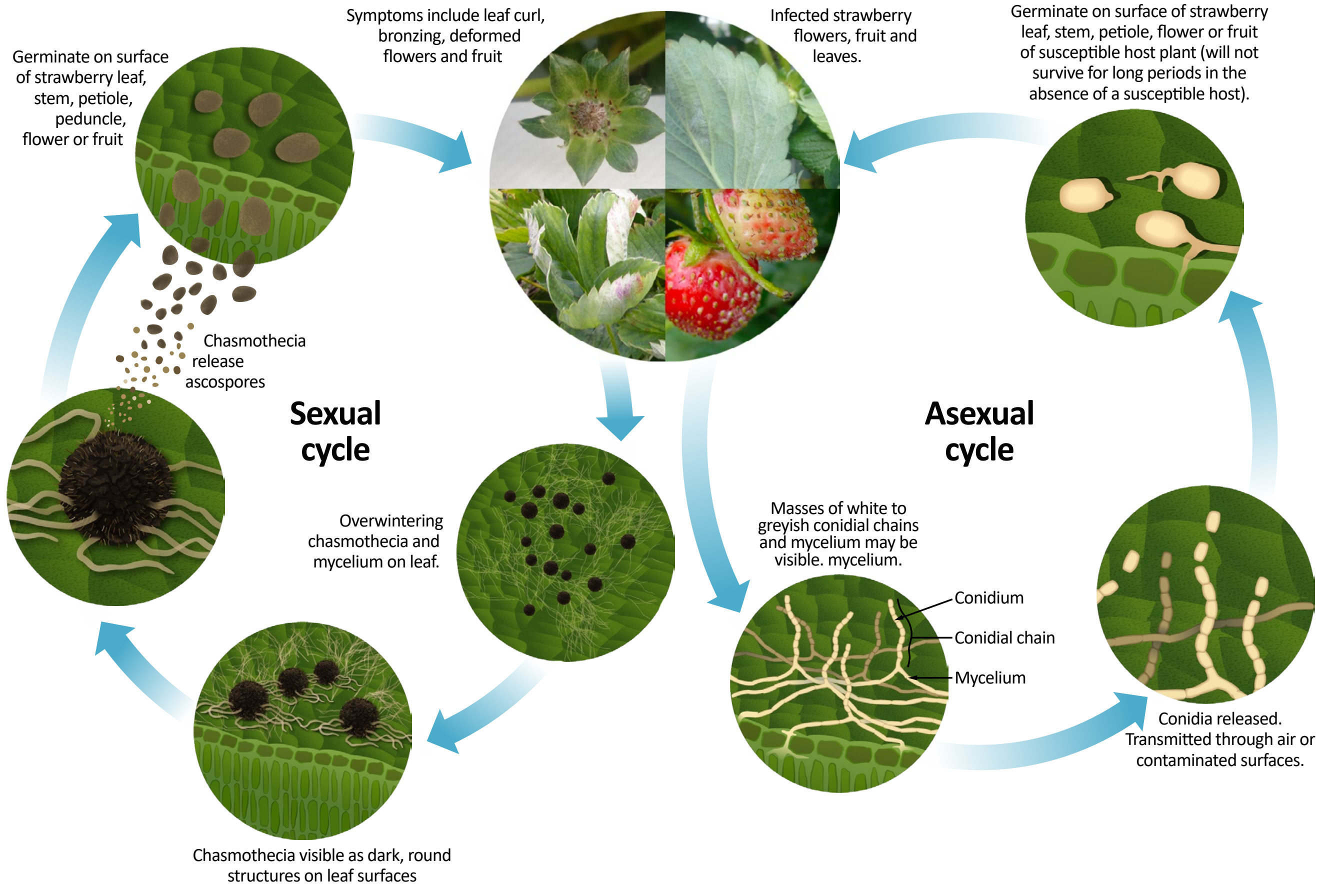

Figure 7. Disease cycle of powdery mildew on strawberries.

Powdery mildews invade the epidermal layer of the plant tissue and form specialized feeding structures, called **haustoria**, that take up nutrients from the plant host.

Some fungi are beneficial. For example, **mycorrhizae** have a symbiotic relationship with plant roots. These fungi aid in nutrient uptake and increase surface area of roots, which increases water and mineral uptake. The plant then provides sugars to the fungus. Many fungi have been developed as **biopesticides**[1] to suppress arthropods and plant pathogens.

Oomycetes

Oomycetes or water moulds, are often mistaken for true fungi. They may live off decaying matter or as parasites living on plants. Unlike true fungi, oomycetes lack chitin in their cell walls. Oomycete pathogens can infect all plant parts and incite a wide range of symptoms including:

- root rot
- wilt
- crown or stem lesions
- angular yellowing of leaves
- dark blotches on leaves, stems and fruit
- chlorosis
- blight
- necrosis

Some oomycete species can form conspicuous mould masses on the underside of leaves, like those causing downy mildew.

Biology of Oomycetes

Like fungi, oomycetes can reproduce sexually or asexually and the various life cycle stages include:

- mycelia
- sporangium and **zoospores**
- **oospores**

Figure 8 illustrates an example of the disease cycle of Pythium root rot and damping off on greenhouse peppers.[3] In this case, the causal agent of root rot is the oomycete, *Pythium aphanidermatum*. *Pythium* species are soil-borne and inhabit the soil as zoospores, oospores or **sporangia** and as **saprophyte** mycelium (colonizing organic matter). In hydroponic systems, *Pythium* species can be carried to the root zone through contamination of nutrient solutions. During asexual reproduction, sporangia release zoospores, which use two whiplike structures called **flagella**, to move in free water. Sexual reproduction results in the production of nonmobile spores called oospores. When any of these structures contact the roots of pepper plants, under the right conditions, they can germinate and penetrate the host plant.

Bacteria

Most bacteria are single-celled organisms that lack a membrane-bound nucleus and other internal structures, which means their genetic material is not separated from the rest of the cell. They are diverse in size, shape, habitat and metabolism.

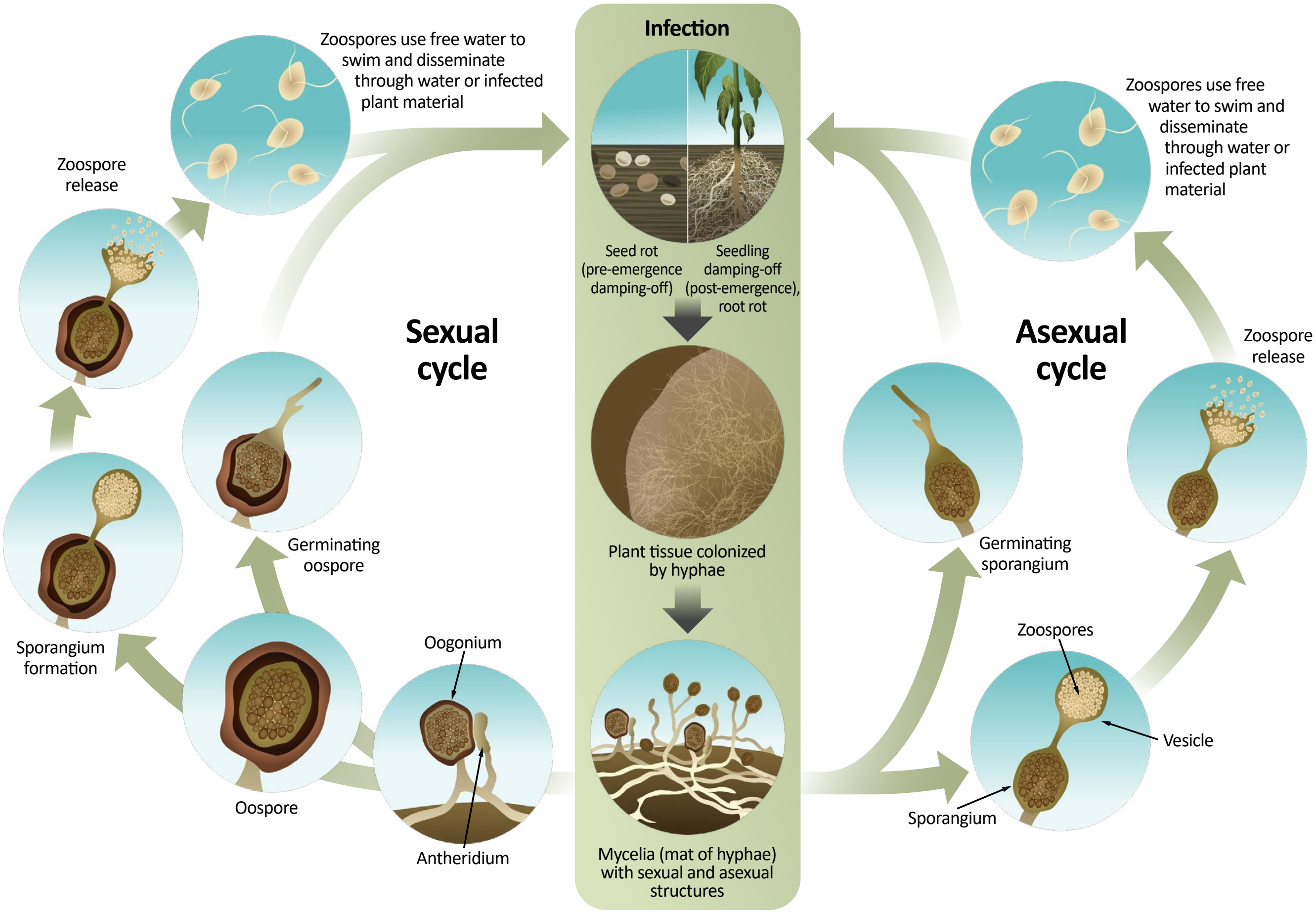

Figure 8. Disease cycle of Pythium root rot and damping off on peppers.

Bacterial pathogens can infect all plant parts and incite a wide range of symptoms including:

- greasy, water-soaked spots or lesions on plant tissue with distinct yellow edges around spots or lesions (commonly referred to as a halo)
- stem rot
- cankers
- blight
- wilt

Biology of Bacteria

Bacteria reproduce (often at a rapid rate) through binary fission, where a single cell divides into two new cells. Each bacterium grows and divides independently of another.

Figure 9 illustrates an example of bacterial wilt on greenhouse cucumbers.[62] Striped and spotted cucumber beetles, *Acalymma vittatum* and *Diabrotica undecimpunctata*, respectively, are the primary **vectors** of the pathogen, *Erwinia tracheiphila*, responsible for bacterial wilt. The bacteria overwinters in the stomachs of adult cucumber beetles. Transmission occurs when the beetles feed on cucumber plants and deposit **frass** containing *E. tracheiphila* near feeding wounds or floral nectaries. The bacteria inhabit the xylem of the plant, multiply through binary fission and produce ooze. The obstruction of the xylem vessels, blocking the movement of water, results in wilting of leaves and stems, foliar necrosis and eventually plant death. **Mechanical transmission** through handling of the plants has also been implicated in the spread throughout the crop.

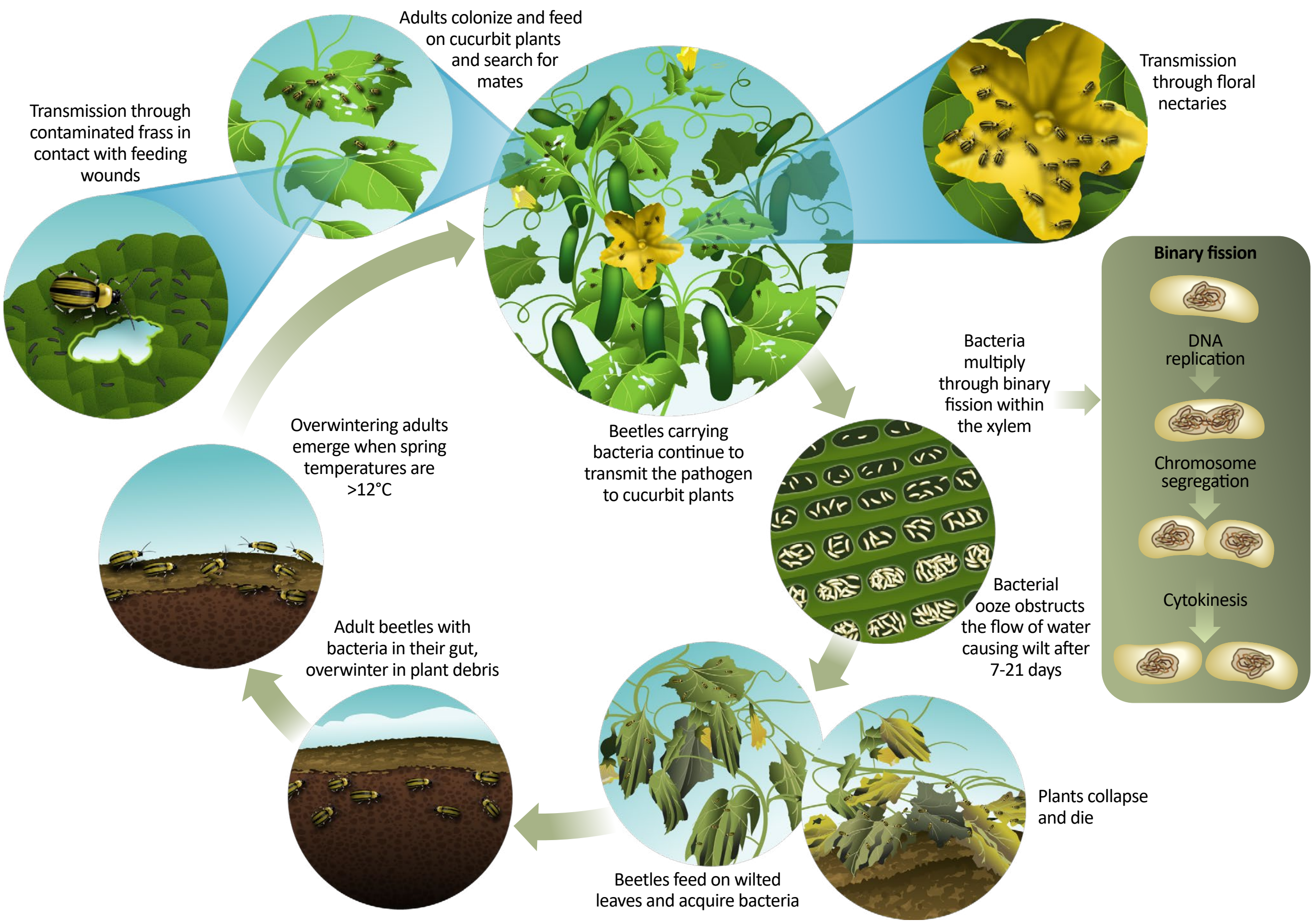

Figure 9. Disease cycle of bacterial wilt on cucumbers.

Aggregates of bacteria may contain several different species, including those found in **biofilms**. Biofilms may include non-pathogenic and pathogenic species and if left unmanaged can clog irrigation systems and provide protection for pathogens.

Gram's staining reaction is used to help identify bacteria, where the bacteria are put on a glass slide and treated with a staining compound. Those that react and stain are considered **gram-positive**, whereas if there is no staining of the bacteria, they are considered **gram-negative**. Gram-positive bacteria have a thick cell wall and lack an outer membrane. Gram-negative bacteria have a thin cell wall surrounded by an outer membrane. Both gram-positive and -negative bacteria may also be surrounded by an outer matrix called a capsule. An example of gram-positive bacteria is *Bacillus thuringiensis* (Bt), an important beneficial agent for managing pests such as loopers. An example of a gram-negative bacteria is *Erwinia tracheiphila*.

Growth Curve of Microorganisms

There are four basic phases of **microbial** growth (Figure 10).[9] Once a population is in an environment conducive to growth, they will adapt and produce proteins (lag phase), then they rapidly grow.

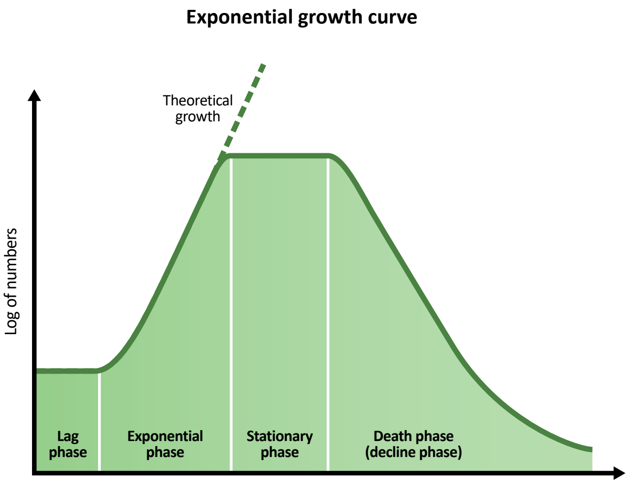

Figure 10. Exponential growth curve of microorganisms.

Nutrients are metabolized until they are depleted after which growth becomes limited (logarithmic/exponential phase). This triggers a reduction in metabolism and consumption of non-essential proteins (stationary phase). Finally, all nutrients are depleted and the organism dies (death phase). Management of microbial plant pathogens should occur during the lag phase. Strategies for management will be discussed in Chapter 2, *Integrated Pest Management.*

Viruses and Viroids

Viruses are much smaller than the previous pathogens described and can only be seen under an electron microscope. Most plant viruses have an RNA genome, but some have DNA that are found inside a protein coat (capsid) and sometimes surrounded by a membrane envelope. They are very diverse in shape and structure. They are obligate parasites and need a living host to survive and replicate (make more viral particles). The route of transmission and spread may differ between viruses. Another pathogen of greenhouse crops is viroids. A viroid is smaller than a virus and consists of a small RNA molecule that does not have a protein coat. Viroids are more common in perennial fruit production systems than in greenhouse production systems, like apple hammerhead viroid or peach latent mosaic viroid.

Viruses can infect all plant parts and incite a wide range of symptoms including:

- stunting
- crinkled or distorted growth
- mottling and mosaic patterns on foliage

Figure 11 illustrates how the tomato brown rugose fruit virus (ToBRFV) infects plant cells and spreads systemically through a tomato plant.[17],[73] In this case, the long, rod-shaped ToBRFV viral particle **(virion)** does not have a membrane envelope. Once the virion contacts plant tissue, it can enter plant cells through natural openings or surface wounds.

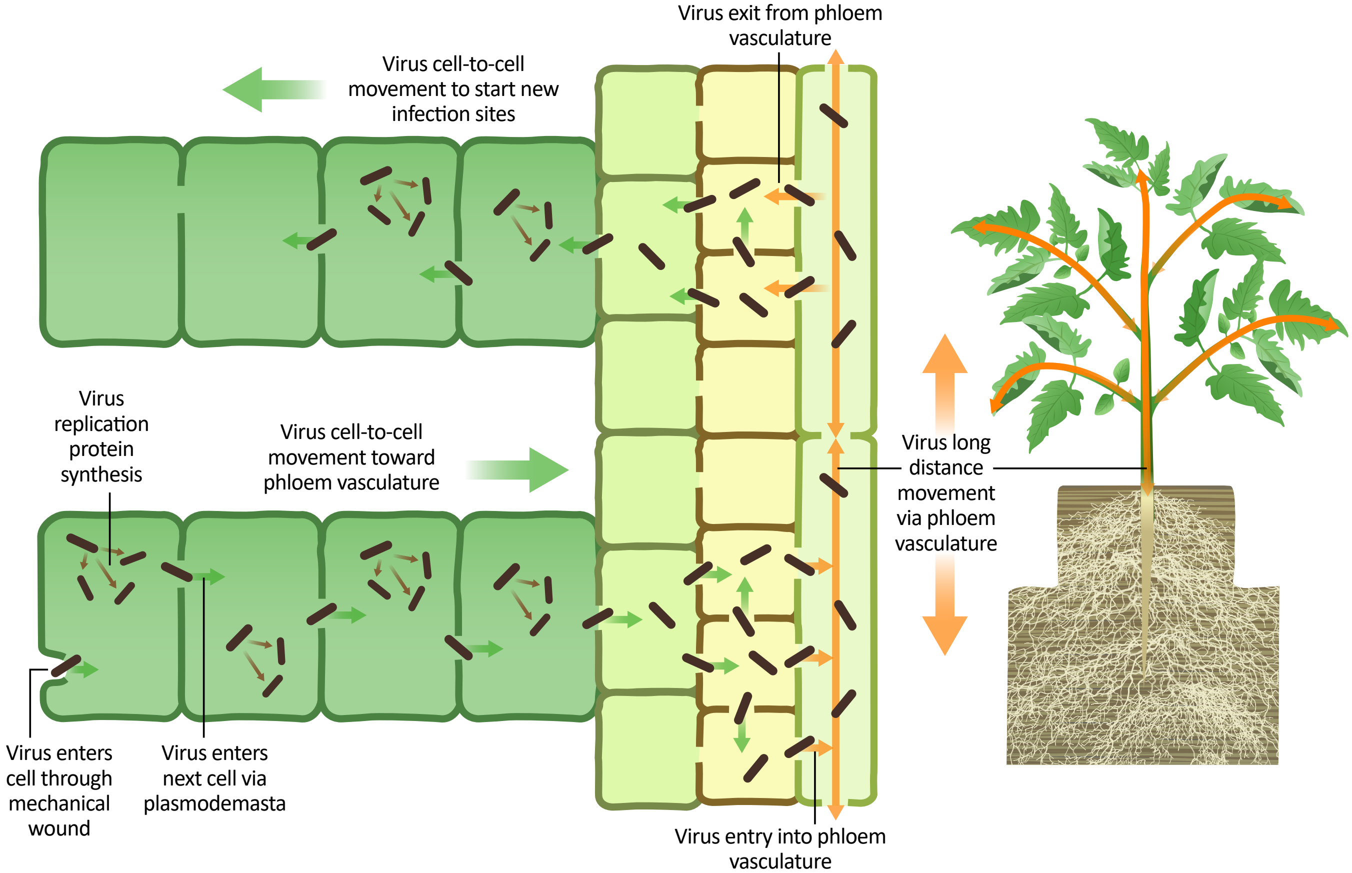

Figure 11. Viral movement through plant structure. Initial infection and systemic spread of tomato brown rugose fruit virus (ToBRFV) on tomatoes.

Once a virus has entered a plant cell, the genomic RNA is translated by host factors to produce viral proteins. These newly produced **viral proteins** will then initiate the replication of viral genomic RNA through further interactions with host proteins and membranes. Once the virus has replicated its RNA and produced enough protein, new virions will form, allowing further transmission of the virus through the plant. Virions move from cell to cell through the **plasmodesmata**, which are basically the connections between cells. Virions can spread systemically throughout the tomato plant through the plant **vasculature**, particularly through the **phloem**.[17] Almost every aspect of plant virus replication and movement depends on interactions with host factors to complete the cycle.

Transmission pathways can also differ between plant viruses. Understanding how a virus enters a production facility is critical for risk mitigation. For example, ToBRFV can enter production greenhouses through several pathways including:

- contaminated seed
- seedlings
- surfaces
- people[23],[64],[65]

After successfully infecting a tomato plant, ToBRFV is easily spread mechanically through employee contact with plants or contaminated equipment.[37]

On the other hand, viruses can also be beneficial. **Bacteriophages** are viruses that infect bacteria. **Baculoviruses** are viruses that infect arthropods. There are some bacteriophages and baculoviruses registered as biopesticides[1] in Canada and used against bacterial diseases and arthropod pests. Some research on viruses attempts to identify mild strains of certain viruses that can be used to vaccinate plants against more severe strains.

Common Pathogens of Greenhouse Fruits and Vegetables

Appendix B provides a list of common plant pathogens of greenhouse fruits and vegetables in Ontario.

Disease Triangle

Understanding the disease triangle is important for evaluating and managing plant diseases. Three factors are necessary for plant disease development (Figure 12):

- a pathogen
- a susceptible host
- an environment favourable for disease development[46]

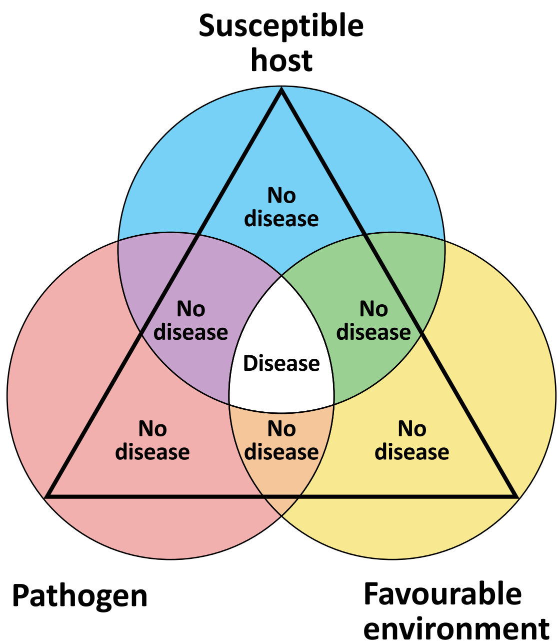

Figure 12. The Disease Triangle.
Source: Department of Plant Pathology of the University of Wisconsin-Madison, USA

All three factors need to occur simultaneously for plant disease to develop. An organism or agent is considered pathogenic when it can cause damage to a host (in other words cause disease in a plant). A **susceptible host** is one which that specific pathogen can infect resulting in disease. For example, a specific tomato cultivar that is susceptible to powdery mildew. A favourable environment for disease development provides conditions that allow the pathogen to thrive and reproduce. Greenhouse and indoor production can be viewed as a microenvironment that is distinct from its surroundings. Within these production systems, there are additional microenvironments throughout the plant canopy and within the root zone. In the context of the disease triangle, the environment refers to the **growing medium environment** in which the roots grow and the **above-substrate environment** where shoots, leaves, flowers and fruits are produced.

Characteristics of the growing medium environment that must be considered to reduce plant disease risk include:

- temperature
- pH
- nutrient levels and their balance
- **electrical conductivity (EC)**
- moisture-holding capacity
- drainage
- oxygen content

Characteristics of the above-sustrate environment that must be considered to reduce plant disease risk include:

- light levels
- temperature
- air-movement
- relative humidity (RH)
- air quality

Disease management focuses on manipulating one or more of the three factors of the disease triangle to prevent disease development. For example, reducing host susceptibility by using a **tolerant** (not immune) host, the susceptible host portion of the triangle will be reduced. Thus, a lower level of disease will develop than with a fully susceptible host. Alternatively, using fully **resistant** (immune) cultivars eliminates the susceptible host and reduces the triangle to a flat line. In this case no disease will develop. See *Host Plant Resistance,* Chapter 2 for more details.

Disease does not occur instantaneously, rather it progresses over time. Depending on the pathogen, this could happen in a few days or a few weeks. This is important in the context of greenhouse production, where crop cycles are typically longer than in the field. Therefore, implementing management strategies early in the disease cycle will increase the likelihood of success.

Vector-Borne Diseases

A vector is an organism that transmits a pathogen from one organism or source to another. Many organisms can vector plant pathogens,[25] including:

- arthropods
- fungi
- bacteria
- nematodes
- mammals

These vectors may be the primary mode of transmission or they may be in addition to other modes of transmission. Some viruses depend on vectors to spread from plant-to-plant.

Arthropod Vectors

There are three main ways in which arthropods acquire and transmit plant pathogens:

- Coming in contact with the contaminated surface of an infected plant and carrying pathogen on their body surface.
- Feeding on infected plant tissue and carrying pathogen on or within their mouthparts.
- Ingesting pathogen **propagules** through plant sap and releasing them through feeding or defecation.

Common insect vectors include **hemipterans**, such as aphids, whiteflies and thrips, all of which have piercing-sucking mouthparts.[29] But bees, fungus gnats and some species of leaf-feeding beetles can also vector pathogens. A wide range of insect species can acquire and transmit pathogens on the outside of their bodies. For example, spores of powdery mildew can attach to any insect that walks through a mass of growth on the plant surface, spreading it to new parts of the plant or to uninfected plants. When the pathogen is acquired internally, these insect species tend to be more specialized for the pathogen. For example, as mentioned previously, cucumber beetles (striped and spotted) are the primary vectors of bacterial wilt in cucumbers.[62]

Transmission of viruses by insects can be classified into three categories: non-persistent, semi-persistent and persistent.[31],[63],[68] These depend on the acquisition time, **latent period** between uptake and ability to transmit to a new host and retention time. The use of insecticides and their efficacy to prevent transmission to crops by arthropod vectors varies depending on the transmission type.

Non-persistent viruses require relatively short periods of feeding time (seconds to minutes) by the insect to acquire enough virus to transmit. These viruses are usually borne on the mouthparts. For example, cucumber mosaic virus (CMV) is a non-persistent virus transmitted by aphids and cucumber beetles.

Semi-persistent viruses require longer times than non-persistent viruses for feeding (minutes to hours) by the insect and are usually borne in the **foregut**. For example, beet pseudo yellows virus (BPYV) is a semi-persistent virus transmitted by whiteflies.

Both non-persistent and semi-persistent viruses do not have a latent period and are typically retained by the insect for a very short period of time.

Persistent viruses may require longer periods of feeding time (hours to days) to acquire the virus but are sometimes passed along to their offspring. These viruses exist in the mid- and **hindgut, hemolymph** (analogous to insect blood) and salivary glands. These viruses have a latent period (hours to weeks) and are retained for anywhere from days to the lifespan of the vector. An example of a persistent virus is tomato spotted wilt virus (TSWV), for which the larvae of western flower thrips, *Frankliniella occidentalis*, can acquire the virus and efficiently continue to transmit it through their entire life. In this case, the thrips do not pass it along to their offspring.

Like insects, some mites can also acquire and transmit plant pathogens.[48] However, a common greenhouse pest, two-spotted spider mites, have not been found to transmit plant viruses.

Beneficial insects have also been explored as vectors of beneficial pathogens, such as bumblebees and mites to distribute the beneficial fungi, *Beauveria bassiana*.

Microbial Vectors

Some species of fungi are responsible for vectoring plant diseases.[10] Most often these are **soilborne fungi**. For example, *Rhizoctonia solani*, a causal agent of root rot, can also acquire and transmit cucumber mosaic virus (CMV).[2]

Some plant pathogens are spread with the help of multiple vectors. For example, melon necrotic spot virus (MNSV) can be transmitted to cucumbers by insect vectors, such as cucumber beetles and root-inhabiting fungi, such as *Olpidium bornovanus*.[70]

Human Vectors

Mammals, including humans, can also be vectors of plant pathogens. As seen with mechanically transmitted diseases, such as bacterial canker, *Clavibacter michiganensis,* or ToBRFV, people that come in contact with infected plants can physically transmit the pathogen through contaminated hands or clothes. This concept is especially important for employees that handle plants regularly or those visiting multiple greenhouses. These risks can be mitigated through **biosecurity** programs and workflow management. See *Cultural Management*, Chapter 2 for more details.

For best results manage the plant pathogens that are primarily transmitted by other organisms through multiples strategies including targeting the vectors.

Native Versus Non-Native Invasive Pests

Native (indigenous) pests in Ontario are organisms that are natural to this province and cause damage to cultivated host plants. **Non-native (exotic or alien) invasive pests** are organisms that have been introduced to Ontario from other regions in Canada or other countries or continents and have negative impacts to ecosystem health and to people. Not all non-native species are considered invasive. Sometimes, these non-native, invasive species are regulated by the *Canadian Food Inspection Agency (CFIA)* under the *Plant Protection Act* in an effort to prevent the establishment or minimize their economic and environmental impacts. For more information, see the *List of pests regulated by Canada*.[14]

Mechanisms of introduction of non-native, invasive species include movement of commodities, arrival of a transport vector and/or natural spread from a neighbouring region.[33],[71]

During the early stages of invasion, exotic pests may lack natural enemies and there may not be pest control products registered for their control. Conversely, many native pests have established populations of natural enemies. Mitigating the risk of non-native invasive pests should therefore focus on managing high-risk pathways for introduction and spread.

CHAPTER 2

Integrated Pest Management

Integrated pest management (IPM) is an approach that seeks to apply multiple available management tools and strategies to try to keep populations of harmful pests below an **economic injury level (EIL)** in cost-effective and environmentally rational manners. In most cases, the goal of an IPM program is not to eradicate pests through pesticide spray programs. Instead, it promotes the integration of multiple strategies to reduce a pest population to an acceptable level that minimizes its economic impact.[56],[60]

Economic Impacts

Yield potential and minimizing economic impacts are important considerations in IPM programs in most food crops. Economic injury level is a measure of a pest population that causes economic damage.[57],[60]

Factors that influence the EIL are:

- cost of management of pest
- market value
- injury units
- damage
- proportional reduction in pest pressure

To avoid incurring significant economic losses, an **action threshold (AT)** (or **economic threshold**) can be used to determine the timing of initiating a “management” action. The timing of the action is important as it defines an appropriate timeline for a reduction in pest pressure before reaching the EIL. ATs can be determined by research or based on experience. The ATs may also differ between pest species, crop species and production systems. For example, one species of thrips may have an AT of 10–12 thrips per flower in greenhouse peppers, while a different species of thrips may have an AT of 4–6 thrips per flower. Accordingly, EIL and AT can be set by individual greenhouse operators, especially if they have access to an extensive and crop-specific data set from past monitoring and management programs, that will help predict the optimal timing for initiating management tactics.

Reducing Reliance on Pesticides

There are several reasons to use AT and other IPM techniques to reduce reliance on pesticides in greenhouses:

1. Over application or misapplication of pesticides can lead to environmental pollution and groundwater contamination.

2. The potential exposure of applicators and workers to pesticides and pesticide residues in greenhouses requires a critical evaluation of frequency of use and pesticide safety during application.

3. Pests can develop resistance to pesticides. Developing and registering new pesticides takes significant time and resources. It is essential to limit use of pesticides to reduce development of resistance in pests.

The best approach to slowing down the development of resistance is using a combination of strategies, reserving pesticides as a last resort. Adopting an IPM approach minimizes emphasis on pesticide use. This in turn reduces adverse human and environmental health effects, reduces residues on food and delays pest resistance. As a result, there are often measurable increases in production and quality from applying a well-designed IPM program.

IPM Principles

There are many strategies that can be used successfully in an IPM program. Before planning a specific program, consider the following six principles of plant disease management that can generally be applied to all pests including arthropods.

Exclusion
One of the primary goals of pest management is preventing pests from becoming established in the greenhouse.

Avoidance
Use practices to avoid conditions that promote pest development.

Resistance
Different cultivars have differing abilities to remain healthy or resist attack when a pest is present and/or the environment is conducive to pest development.

Protection/Prevention
Improving plant health through biocontrol, preventative measures can reduce transmission and spread of pests.

Eradication
Though difficult for some pests, this can sometimes be achieved with strict management efforts.

Therapy
Post-infection/infestation treatments can help reduce spread to healthy neighbouring plants and in some cases prevent serious plant injury.

Creating an IPM Program

Each greenhouse operation will likely have their own IPM program, as the "recipe" necessarily varies by crop, location, season and pest tolerance of the operation. Everyone working in crops and throughout the **supply chain** is responsible for implementing or supporting a designated IPM program and should actively coordinate to preventatively reduce pest pressure and pesticide use. This might include adoption of general guidelines and best practices that are specific to individual greenhouse operations. An IPM program includes monitoring for pests and up to four basic prevention/management components: cultural, physical, biological and pesticides (Figure 13).

Each management component is explored in more detail under the following sections:

A. Monitoring

B. Cultural Management

C. Physical Management

D. Biological Management

E. Biopesticides and Conventional Pesticides Management

Components of an IPM Program

All components of an IPM program are important to successful management of pests. Regardless of their primary duties, all employees would benefit from training to understand the signs and symptoms of plant pests and biocontrol agents.

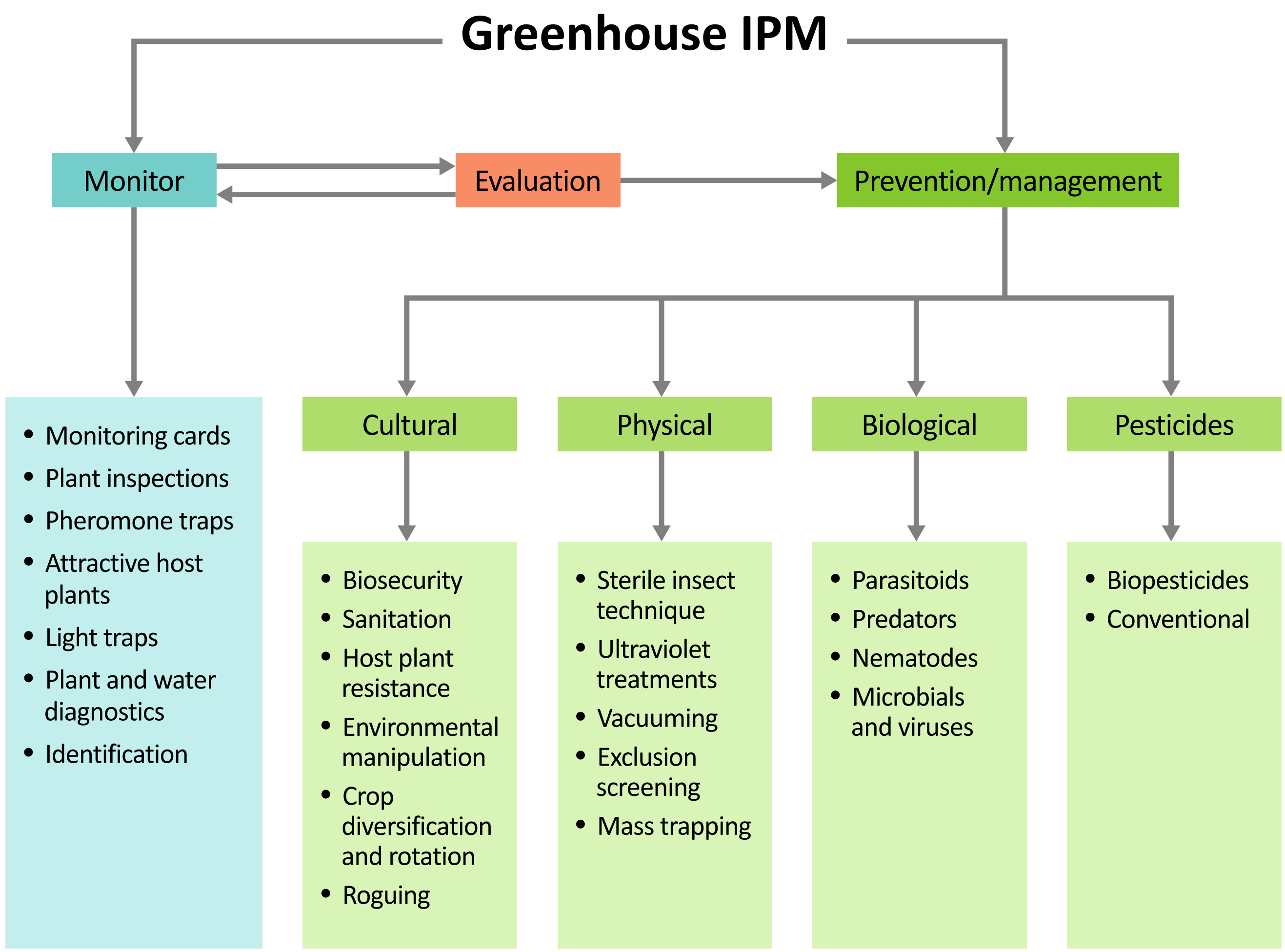

Figure 13. Components of an integrated pest management (IPM) program.

A. Monitoring

Diligent monitoring or scouting should be done at least weekly to provide reliable information to guide pest management decisions. Ideally, the entire greenhouse would be monitored within one week. Realistically this may vary depending on:

- the cultivated crop
- the size of the crop
- the level of pest pressure
- the pest species
- access to labour and equipment

Compared with older crops, young crops may be easier to monitor, with smaller plants, fewer pests and scouts can cover more area in a shorter time. As plants grow, additional time is needed for monitoring using equipment such as scissor carts, so alternating rows each week may be necessary. In some cases, this may mean every fourth row is scouted so the entire greenhouse is covered every four weeks.

Common monitoring strategies and tools include:

- application of sticky traps for monitoring flying insects
- physical plant inspection for signs and symptoms of plant disease and sedentary stages or non-flying pests
- use of selective **pheromone-baited traps**
- attractive host plants and **light traps** to improve early pest detection
- use of molecular methods (for example using polymerase chain reaction or PCR) or immunoassays (for example strip tests) for early disease detection

As well, recent advancements in technology have started incorporating artificial intelligence (AI) and imaging recognition software that can both identify and count pests on **sticky cards**.

In the absence of or in addition to such technologies, some basic ways to identify pests and record details of their occurrence include using:

- writing tools such as paper/pen and clipboard or digital tablets to keep detailed records
- hand lenses and/or cameras (phone/microscope) equipped with macrophotography capacity
- **flagging tape** to mark infested or suspicious plants to revisit with treatment option or re-evaluate need for future treatment

Sticky Cards

The most common greenhouse monitoring tool is using sticky cards to trap many species of flying insects. The cards come in a range of sizes and colours including yellow, blue, white and green. Yellow sticky cards are especially good for a wide range of insects including adult whiteflies, thrips, leafminers, fungus gnats and winged aphids. If a wide range of pests are present, use yellow sticky cards. Generally, few biocontrol agents are captured on these cards.

When using sticky cards, it is important to provide adequate coverage. Use a minimum distribution rate of one card every 100–200 m^2 (1/100 m^2 in small areas; 1/400 m^2 in larger areas). Choose the higher or lower end of this range based on the size of the operation being monitored, the pest incidence and the time of year. Using more sticky cards assists in early detection at low population densities. Change cards as needed to make it easy to count and record the number of insects caught every week. Sticky cards may lose adhesiveness after approximately 12 weeks in a hot greenhouse. To avoid double counting insects, use a permanent marker to mark off the insects or circle them.

Cards should be placed near insect activity based on their preferred food source or areas where you would expect early infestations or initial points of entry (Figure 14). Many insect pests prefer young growth, so cards are often placed near the top of the plant.

Figure 14. (A) Yellow sticky cards and (B) Blue sticky cards used for monitoring flying insect pests in greenhouse crops.

Information to record on sticky cards from weekly observations includes:

- ✓ date or week number
- ✓ card location
- ✓ identity of insects (are they significant to the crop?)
- ✓ quantity of insects
- ✓ compare numbers on cards with observations on the plant to evaluate trends or sudden influxes of pests
- ✓ note changes in weather or greenhouse climate settings

Plant Inspections

Visual plant inspections are essential for monitoring the presence of multiple species and stages of sedentary pests such as mites, wingless aphids or immature stages of whitefly, thrips and loopers. As well, plant disease signs and symptoms should be recorded such as wilting or masses of powdery mildew.

Adopt a regular sampling pattern that provides good coverage of the whole greenhouse, including entry points and areas of concern. Early detection allows for timely interventions to prevent or delay the spread of pest populations to healthy neighbouring plants. Timely interventions may include removal of infested/infected plants or using spot applications of biocontrol agents or pesticides, thereby decreasing costs associated with management of pests.

Inspecting plants should include visually scanning plants, flipping leaves at random to observe activity on the underside of the leaf and checking flowers which are attractive to many pests such as thrips. Scouts should move down the row at a reasonable speed. Observations should include indicators of biocontrol establishment, such as desired biocontrol agents present at different life stages in pest colonies. Look for other signs of pests such as feeding damage, frass (insect excrement), white moult skins of aphids or honey dew excreted from aphids and whiteflies. Make note of discoloured plants or concerns regarding general plant vigour. For wilted plants, inspect stems for breakage and roots for symptoms of rot.

If a pest is observed and there is a need to apply a treatment or recheck the area in the future, flagging tape can be used to mark individual plants and mark the beginning of the row where the plant was observed. Some programs use different colours to mark different pests. For example, blue for whiteflies, pink for two-spotted spider mite and orange for suspected disease. Writing the week number or date on the flagging tape can help with future observations and evaluating the success of treatments applied.

Weekly observations of plants should include:

- ✓ date or week number
- ✓ location in the greenhouse
- ✓ crop species and cultivar
- ✓ identity of insects and mites (are they significant to the crop? a pest or a biocontrol agent?)
- ✓ quantity of insects (rough estimates of infestation levels such as low numbers vs hot spot)
- ✓ stage of insects (such as adults, pupae, larvae/nymphs, eggs)
- ✓ extent of damage
- ✓ biocontrol establishment (are all life stages present?)
- ✓ pesticide efficacy
- ✓ location on the plant (flowers vs leaves)
- ✓ correlate observations on the plant with numbers on the sticky cards
- ✓ note unusual colour of leaves or stems
- ✓ note whether number is a trend or sudden influx
- ✓ note effects of weather or environment in the greenhouse

Light Traps

Light traps also provide an easy-to-use, non-chemical alternative for attracting nocturnal (night-flying) moth pests such as adult loopers. Light traps use a combination of black-light lamps for attracting insects and a low-voltage electrocutor that surrounds the lamps. These lamps emit long-wave ultraviolet (UV) radiation around 365 nanometres (nm). They also emit some visible light in the range of 430–540 nm. Ultraviolet light is the most effective part of the light spectrum for attracting nocturnal moths.

Consider the following factors when using light traps:

Size

The bigger the trap, the greater its power to attract moths. Most traps can attract moths within a 40–50 m radius.

Location

Ideally, place traps in locations best suited to their attracting range. However, because convenience tends to dictate their location, most greenhouse employees place them along walkways. In either case:

- Place a large sticky board or a receptacle containing soapy water below the trap to catch insects.
- Place traps high enough so that plants don't block the light emitted from traps or hinder access by smaller moths.
- Place traps just above the plant canopy.

Maintenance

To maintain trap efficiency, inspect and clean light traps regularly.

Bumblebees

Light traps may attract and kill bumblebees. To avoid or minimize trapping of bees, use a timer so lights are turned on at dusk after most bees have returned to hives and turned off at sunrise. Some biocontrol agents may also be attracted to the lights so be mindful if using agents that are active at night.

Pheromone-Baited Traps

Pheromones are chemical compounds released by organisms that elicit an immediate response such as sexual attraction, alarm or recruitment behaviours or cause physiological changes in the insect. Species-specific pheromone lures can be used to facilitate early detection. Insects in the vicinity of the pheromone lure may be greatly attracted to the trap and observed earlier than they would otherwise. Pheromone-baited traps (pheromone lure with a sticky card) are often used for early detection of pepper weevil, *Anthonomus eugenii* (Figure 15).

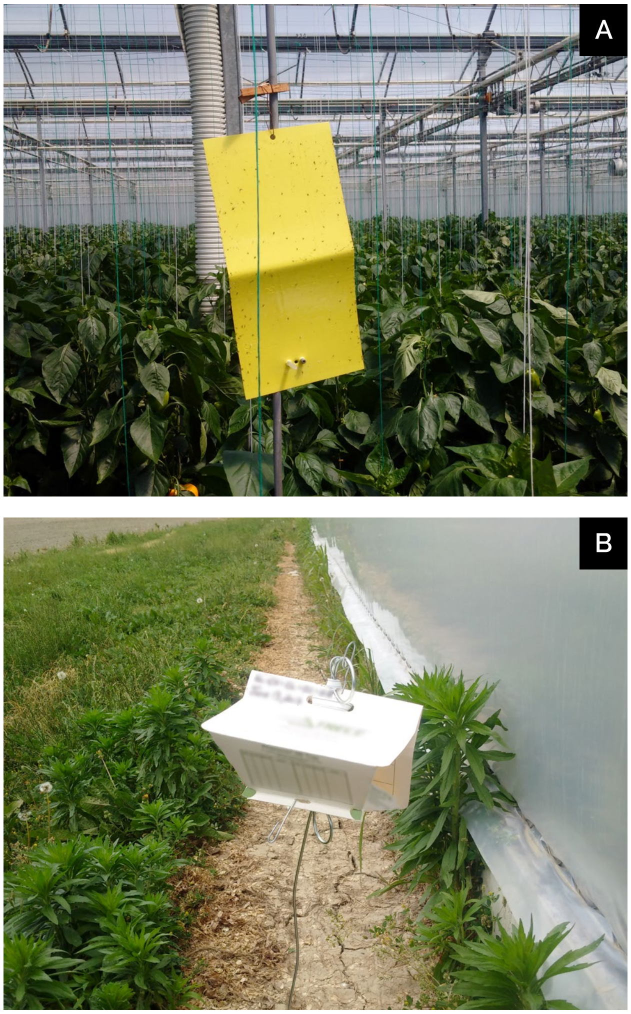

Figure 15. (A) Pepper weevil pheromone-baited sticky trap used for monitoring in greenhouse peppers. (B) Looper pheromone-baited trap used for monitoring outside the greenhouse.

Attractive Host Plants (Indicator Plants)

Occasionally a particular plant species can be more attractive to pests than the cultivated crop. These attractive host plants can be used as "indicator plants" as an early warning system. Depending on the crop being grown, some options for attractive host plants include eggplant for whiteflies, marigolds for thrips or beans for two-spotted spider mites (Figure 16).

Figure 16. Bean indicator plants used for monitoring two-spotted spider mite in greenhouse tomatoes.

Identification/Diagnostics

Proper identification of arthropods and diagnosis of plant disease is important for making informed management decisions. For example, root rot symptoms may look similar visually even if there are different causal agents, but treatment options may be different for a true fungus like *Fusarium oxysporum* compared with an oomycete like *Pythium aphanidermatum*.

Sometimes arthropod identification can occur on-site when the distinguishing features are obvious and can be observed through a hand lens or microscope. More subtle or complex distinctions may require a professional taxonomist or the use of genetic diagnostics such as barcoding or sequencing. For example, it is difficult to distinguish between tomato looper, *Chrysodeixis chalcites,* and soybean looper, *Chrysodeixis includens,* on-site and requires close inspection of insect genitalia or sequencing to identify at the species level. Since some treatment options may provide greater efficacy for one species, this distinction is important.

Tools for disease diagnostics may include visual inspections for conspicuous pathogens like powdery mildew or obvious symptoms like late blight, rapid tests for some bacterial or viral pathogens or use of a diagnostic laboratory in your area to confirm species or causal agent. Examples of rapid tests are **immunoassay test strips** that react with antibodies in plant tissue that indicate the presence of a specific plant pathogen via a visual indicator.

Disease diagnosis can be proactive or reactive. **Proactive sampling** is random or frequent sampling prior to symptom observations. For example, a greenhouse could monitor for tomato brown rugose fruit virus (ToBRFV) by sampling nutrient solution regularly and testing for ToBRFV through PCR, sequencing or other **laboratory immunoassays**. **Reactive sampling** would occur once symptoms are observed to confirm the organism causing the damage.

Degree Days

In some cases, we can predict life stage events using knowledge about temperature-dependent development. These predictions can be done by tracking accumulated **degree days (DD)**. Degree days are heat accumulations using a base temperature (the minimum temperature required for development). Most often this is calculated by taking the average daily temperature and subtracting the base temperature:

$$\textit{Degree Days} = \frac{(\textit{maximum temperature} + \textit{minimum temperature})}{2} - \textit{base temperature}$$

The starting point for DD calculations is determined using a **biological fix (biofix)** date.[72] The biofix date may be a specific calendar date (such as April 1st, where there is confidence that the species of interest has not emerged from their overwintering site prior to this date) or the date of a biological event (such as the point of sustained flight determined by trap captures). Degree day models are cumulative, where daily heat accumulations are added to the previous day(s) accumulations.

An example is a validated DD model that can be used to predict flight patterns of European corn borer (ECB) in southwestern Ontario (Table 1).[5] This model gives us an idea when ECB flight begins, peaks and ends based on moth captures and can be used to guide scouting efforts and management decisions. Degree day models do not exist for all pests and are difficult to develop for pests that have multiple, overlapping generations.

Table 1. Degree day model for European corn borer in southwestern Ontario validated by Baute, 1999

Number of Generations	First Catch[1]	Peak Flight[1]
Bivoltine (2 generations)		
1st generation	150	300–350
2nd generation	700	1050
Univoltine (1 generation)		
1st generation	300	650–700

[1] Degree day accumulations.

Record Keeping and Data Management

Once all information is collected, the data should be used to evaluate whether any action is needed. Good record keeping can provide helpful insight into population increases and management success. There may be obvious trends over time or from one year to the next. These can be used to assist with monitoring efforts, proper timing of management options and prediction of migratory pest occurrences. Using maps can be helpful to give a visual indication of location and spread from week to week. Many digital tools are available now to assist with data collection, management and analysis.

The video *Monitoring for Pests in the Greenhouse*[77] on *ONGreenhouseVegetables.ca* provides additional information.

B. Cultural Management

Management of crop pests through cultural management involves alteration of the production system or practices to reduce pest populations or to disrupt their necessary habitat or environment in or near the crop. Many diverse cultural management techniques can be incorporated into an IPM program in greenhouse production such as biosecurity, **sanitation**, host plant resistance, environmental manipulation and modification of growing practices, crop diversification and rotation and removal of dead and dying plants **(roguing)**.

Biosecurity Plan

Biosecurity is the use of risk mitigation strategies to protect crops from pest damage including preventing introduction and managing the spread of pests. Strategies include identifying and resolving pathways of introduction. Pathways of introduction and transmission into a greenhouse may be different for each pest species.

Common risks include:

- presence of host weeds
- infested or infected organic matter or crop debris
- growing conditions
- imported produce
- mammals

Many of these risks can be mitigated through a comprehensive biosecurity plan using multiple techniques. A biosecurity plan may look different for each greenhouse depending on the crop grown, production methods, structure and pest threats.

Pest mitigation is most successful when a biosecurity plan is implemented at all parts of a supply chain. This includes, but is not limited to, propagators, producers, packers, importers, waste disposal, suppliers, consultants and government (Figure 17).

Figure 17. Signs posted at entry points can remind greenhouse staff and visitors to follow biosecurity procedures.

A detailed *Greenhouse Vegetable Sector Biosecurity Guide* by the *Canadian Food Inspection Agency* can be used to assist in the development of a biosecurity plan.[12]

Cleaning And Sanitation

Sanitation is a necessary part of any IPM program and is a continual, year-round process.[53] These measures have a direct impact on pest levels. Generally, sanitation involves the removal of infested materials and potential sources of infestation, followed by disinfection of surfaces.

For maximum impact, sanitation measures should be practiced at all stages of production, beginning with propagation, all the way to the end of the crop (termination). As well, focus areas and disinfectant choices may differ based on the crop species or pest threats. For example, since ToBRFV is easily spread throughout the crop and survives for long periods of time on surfaces, focus sanitation efforts on diligent cleaning of areas, tools and equipment that are at a high risk of contamination through plant sap.[23],[47] This includes surfaces touched by employees after they have handled plants, such as door handles or handrails. Effective detergents and disinfectants are often identified through research for high-risk plant pathogens like ToBRFV.[15],[69]

Various levels of sanitation should be implemented within the greenhouse. During crop production, basic sanitation is used to suppress development of pests. However, at the end of each crop cycle, before re-planting, a major sanitation is needed. This is often referred to as "crop clean out." It entails not only removing all plant material but also subsequently cleaning and disinfecting the greenhouse structure and all equipment used within it. This process minimizes carryover of pests to the new crop, thereby facilitating a clean start in the next cropping cycle.

There are three critical steps to thorough cleaning and sanitizing. They should be completed in the following order:

1

Remove Organic Matter
Organic matter protects pests and can neutralize/inactivate disinfectants.

2

Wash with Detergent, Rinse, Dry
Washing or scrubbing with detergent first can eliminate more organic matter and begin to break down pathogens.

3

Disinfect, Rinse (as needed), Dry
This final step can catch what was missed in steps 1 and 2.

Measures Used During Crop Clean Out

Treat plants prior to removal to eliminate active pests. Remove and properly dispose of:

- Old crop and plant residues. Remove all organic matter and inorganic deposits (including calcium deposits) from all surfaces and objects to be disinfected. Any organic matter or residues present will react with the disinfectant and reduce its effectiveness. Scrub textured surfaces with a detergent or commercial-grade cleaner and a power washer. Shred vines, sweep and vacuum focusing on gaps in the floor covering, walkways, corners, ledges, etc. (Figure 18). Do not pile or spread infested or infected plant material behind your greenhouse.
- Other materials such as clips, slabs, strings, etc. Replace old floor covering when damaged or difficult to clean.

Figure 18. (A) Tomato vines going through a shredder. (B) Vacuuming crop residue.

Areas to clean and disinfect include:

- stock tanks, return/dirty leach tanks, freshwater tanks, pump sets
- emitters stakes: Soak in acid solution for up to 48 hours, rinse well, disinfect, rinse well when specified by the product label. Replace emitters and other parts when damaged or difficult to clean (Figure 19A)
- empty structures: Use a power washer or some specialized equipment on low pressure with a large opening tip. Start at the point of the roof and work down (Figure 19B)
- horizontal surfaces where dust and debris can collect: Heating pipes, rafters, troughs, concrete walkways (Figure 19C)
- tools and equipment: Such as scissor carts, picking crates, wires, machinery, vehicles, forklifts (including forks), pallets, knives and scissors
- other common areas: Offices, washrooms, lunchrooms, packing lines, boiler room. Do not forget door handles, keyboards and other surfaces touched by employees.

Cleaning and sanitizing a greenhouse between crop cycles on ONGreenhouseVegetables.ca provides additional information.[75]

Figure 19. (A) Dirty emitters stakes covered in inorganic deposits. (B) Washing and disinfecting the structure. (C) Washing and disinfecting the troughs. (D) Clean greenhouse ready for planting.

Prior to cleaning irrigation equipment, remember to remove drippers from growing medium, keeping lines slightly charged to maintain moisture. Also disconnect pH and **electrical conductivity (EC)** sensors and remove filters.

Six steps to flushing lines:

1. flush with water
2. flush with acid (such as nitric acid, sulfuric acid, hydrochloric/muriatic acid); check emitter manufacturer for pH requirements.
3. pulse several times at 1-hour intervals for 24 hours
4. flush with clean water
5. flush with disinfectant
6. flush again with clean water when specified by the product label

When washing and disinfecting different parts of the greenhouse, be sure to let soak (wet) for 15–60 minutes. Though longer contact time is generally more effective, be mindful of potential corrosion by disinfectants. Rinse well with water and let dry completely between steps.

Maintain warm temperatures in a crop-free, dry greenhouse to “starve” pests and increase the efficacy of disinfectants. In general, lower temperatures require longer contact times between the disinfectant and surfaces, whereas higher temperatures increase their efficiency two- to three-fold for every 10˚C rise in temperature. Ideally, mix disinfectants in warm water (at approximately 20˚C) and apply the solution to dry surfaces during the evening in a warm greenhouse. Do not use hard water (water with calcium ions more than 300–400 ppm) with disinfectants because it destroys the disinfecting ability of certain chemicals.

Always use the proper concentration of disinfectant as recommended by the product manufacturer. Concentrations that are too weak may not disinfect properly, while concentrations that are too strong may damage the materials that the disinfectant contacts. Always check federal, provincial and municipal regulations when choosing pesticides and disinfectants. It is critical to store, handle, apply and dispose in a proper manner to avoid negative impacts on personal health and safety and the environment. Always check **safety data sheet (SDS)** recommendations before using any product. Check warning labels for required **personal protective equipment (PPE)**. Heat and vent to rid the greenhouse of pesticide residues after clean out to avoid phytotoxicity in your next crop.

Other measures may include use of a heat treatment to remove pest infestations when the greenhouse is empty between crops. Maintaining temperatures at approximately 40˚C and humidity at less than 50% for 3–4 days can help eliminate insect and mite pests. This is easier to accomplish during the warmer months, when these temperatures can be achieved by simply closing the vents. Note that at higher temperatures, plastic fittings may warp.

Replace growing medium when possible. **Solarization** or **steam sterilization** are options to treat growing medium that is reused as is often the case with organic crops.

The temperature and length of time required to kill or denature the target pest may differ between organisms or species. For example, approximately six hours of steam treatments require temperatures ranging from 50˚C for some bacteria to over 70˚C for some fungi to kill or denature the pest. Even higher temperatures may be required to inactivate some viruses.

Avoid overwintering garden or house plants in the greenhouse, since they can harbour pests that could infect the next crop.

Measures Used During Early Crop Establishment and Crop Production

Use pest-free plant material by purchasing clean seed that has been treated (if available) or tested for potential plant pathogens and propagated in a clean facility. Do not bring new plants into the greenhouse until the old crop has been removed and the area thoroughly cleaned and sanitized. Examine all transplants (plants and roots) from the propagator so that diseased or pest-infested plants can be discarded or treated immediately.

Visitors and staff should follow good hygiene:

- Wear disposable coveralls and freshly laundered clothes or uniforms.
- Wear boot covers or change into clean "farm" shoes.
- Wash hands thoroughly. Note that when handling plants, washing hands is not as effective at reducing pest transmission as using and regularly changing disposable gloves.

Hygiene stations can be installed upon entry to ensure all visitors and employees sanitize shoes and hands prior to entry (Figure 20A). Use disinfection mats as foot baths and tire baths (for small vehicles) between greenhouse compartments (Figure 20B and Figure 20C). Routine maintenance of these baths is essential. Follow the instructions on the label of the product being used. Keep walkways and all surfaces clean. Regularly remove and properly dispose of crop residues. Maintain good drainage to eliminate puddles and wet surfaces since these provide ideal breeding sites for fungus gnats and shoreflies. Dip cutting knives in disinfectant (including handles) between plants or at a minimum, at the end of each row to prevent pathogen spread. Keep the greenhouse and its immediate surroundings free of weeds and ornamentals that may harbour pests.

Figure 20. (A) Hygiene station installed at entryway of greenhouse. (B) Footbath. (C) Disinfection mats for small vehicles at entrance to production area.

When handling diseased or heavily infested plants:

- Have employees wear disposable coveralls and gloves.
- Remove dead and dying plants (also called *Roguing*). Place them in bags when removing them from the growing row. Place rogued plants in commercial garbage containers and dispose of them in an area that reduces potential reintroduction.

Disinfecting Recirculated Nutrient Solution
Clean source water mitigates the risk of introduction into the greenhouse through irrigation channels. Disinfecting recirculated nutrient solutions prevents pathogen levels from building over time. There are many types of disinfection systems that can suit a range of situations. See *Nutrient Solution Recycling and Disinfection*, Chapter 7 in Publication 836B: *Production of Greenhouse Fruits and Vegetables in Ontario*.

Host Plant Resistance

Three basic categories define the degree of plant-pest interactions: plants are susceptible, tolerant or resistant. A **susceptible plant cultivar** is one where the pest can establish, reproduce or replicate and results in damage or symptom development. A **tolerant cultivar** may experience less impacts to plant health but does not eliminate the pest population and damage or symptoms can develop at reduced efficiencies. A fully **resistant cultivar** prevents the pest from establishing, reproducing or replicating. Crop plants may be bred with **heritable** pest resistance and thus many commercially available cultivars are resistant to specific plant pathogens. Host plant resistance is particularly effective against viral pathogens, due to their obligate reliance on host factors to complete their life cycle. For example, the *Tm-2*^{2} resistance gene provided stable resistance against tobamoviruses like tobacco mosaic virus (TMV) and tomato mosaic virus (ToMV) until the emergence of ToBRFV in 2014.[40][79] A susceptible plant cultivar is one where the pest can establish, reproduce or replicate and results in damage or symptom development (Figure 21).

Figure 21. A fully resistant cultivar prevents the pest from establishing, reproducing or replicating.

Environmental Manipulation and Modification of Growing Practices

Environmental factors such as light, temperature, relative humidity (RH), air circulation, water, nutrients, growing medium composition, pH and EC can affect not only plants but also the pests that afflict them as well as the biocontrol agents that attack pests. Using environmental manipulation to manage pests is a complex process. Each target pest may respond differently to changes in the growing environment and needs to be assessed carefully.

For example, humidity can play an important role in pest development. Two-spotted spider mites prefer hot, dry conditions and increasing the humidity through overhead misting can help slow their development and population growth. Conversely, higher humidity might increase disease progression for certain pathogens.

To create a well-balanced and healthy-greenhouse environment and reduce plant stress:

- Understand the conditions required for optimum crop growth, the common pests of distinct crop types and the biocontrol agents used to manage them on specific crop types. For more details on environmental requirements, see Publication 836B: *Production of Greenhouse Fruits and Vegetables in Ontario*.
- Be aware that leaf surface temperature can be lower than air temperature due to radiant heat loss.
- Provide good air circulation. Poor air circulation can cause temperature gradients through the crop. It can also lead to free moisture forming on the plants, particularly at night, creating ideal conditions for powdery mildew and gummy stem blight, *Stagonosporopsis cucurbitacearum* (previously known as *Didymella bryoniae*) infections.
- Avoid all extremes as much as possible. Rapid changes in temperatures and relative humidity, especially between day and night, can encourage disease progression. Over-fertilization promotes *Fusarium solani* and *Fusarium oxysporum* infection, while the combination of very high or low temperatures and overwatering favours the development of *Pythium* species.
- If **foliar diseases** are an ongoing problem, review temperature, relative humidity, air circulation patterns and watering practices. The incidence of foliar diseases can often be reduced by maintaining higher nighttime temperatures or higher minimum pipe temperatures, along with proper venting.
- Ensure that crop maintenance is completed sufficiently early in the day to allow wounds to dry, making them less prone to infection. For example, de-leafing wounds are a common entry point for Botrytis grey mould, *Botrytis cinerea*.

Crop Diversification and Rotation

Growing a single species in a large area (also called monoculture) can be a significant challenge for IPM programs. Although some pests thrive in **monocultures**, this is not an ideal environment for many natural enemies of pests that may rely on various sources of food for insuring their fitness. For example, adult parasitic wasps of many species need nectar to maximize their lifespan and reproduction rates. Additionally, plant diseases such as ToBRFV, can spread quickly within a large monoculture of greenhouse tomatoes. Since ToBRFV can be persistent in the environment and difficult to eliminate, crop diversification and rotation can reduce the impacts of this virus.

In some cases, persistent and economically damaging pests can be managed by switching to a non-host crop. Greenhouse operations that grow more than one crop and are divided by compartments could rotate areas of the greenhouse to reduce pest pressure. For example, if growing cucumbers and tomatoes in two different sections of the greenhouse, these could be switched annually to minimize impacts of ToBRFV. It is also interesting to note that some beneficial arthropods such as *Orius insidiosus* reproduce much more readily on crops like peppers relative to tomatoes. Thus, to maximize their biocontrol potential, growing preferred plant species next to less preferred ones can have an overall beneficial impact on IPM programs.

Roguing

Carefully removing infected or infested plants and/or growing medium can minimize the spread of plant pathogens or arthropod pests to neighbouring plants. To do this, follow biosecurity protocol to avoid further spread while removing plants by wearing protective gear and frequently disinfecting of tools. First, cut the infected/infested plant out from its support and disinfect scissors (including the handles) (Figure 22A). Next, cut the block free from the slab and disinfect the knife (Figure 22B). Finally, carefully place the infected plant inside a sturdy garbage bag, keeping the garbage bag's exterior clean and seal the bag (use assistance for this step if available) (Figure 22C).

Figure 22. Steps to remove infected/infested plants. (A) Cut the infected/infested plant free from its support and disinfect scissors (including the handles). (B) Cut the block free from the slab and disinfect the knife. (C) Carefully place the infected plant inside a sturdy garbage bag, keeping the garbage bag's exterior clean and seal the bag. *Source*: In collaboration with Ontario Greenhouse Vegetable Growers.

C. Physical Management

Physical pest management strategies consist of either active or passive techniques.

Examples of active methods are:

- vacuuming
- ultraviolet treatments (UV)
- irradiation/**sterile insect technique (SIT)**

Examples of passive methods are:

- installing **exclusion screening** on vents
- **mass trapping** pests using light traps, sticky traps or trap plants

Active Physical Management Techniques

Vacuuming

Although labour intensive, carefully vacuuming areas of high pest pressure for insect pests like whiteflies, can be an effective tactic to rapidly reduce adult populations.

Ultraviolet-C (UV-C)

Foliar treatments using UV-C light can help with management of pests such as powdery mildew or two-spotted spider mite. These treatments are best done at night to minimize worker exposure and maximize the effectiveness of the treatment. High doses or frequent applications of UV treatments can damage plants and impact yield. The effect of UV-C dose, dosing interval and timing of application may differ by crop.[55] The non-target impacts of UV-C treatments to biocontrol agents should also be considered and avoid applications where they are most abundant when possible.

Sterile Insect Technique (SIT)

The SIT is a form of genetic pest management that involves sterilizing a large number of males of a particular target insect species and releasing these into the target control area. Following this release, sterile males can mate with an unsterilized female, that may subsequently produce non-viable eggs. In ideal situations, the targeted insect populations will be significantly reduced in treated areas. As of May 2024, this technique has not been applied in greenhouse fruit and vegetable production in Ontario, but proof of concept has been demonstrated for some pests such as the successful sterilization of the pepper weevil through irradiation.[4]

Passive Physical Management Techniques

Exclusion Screening

Installing screens over vents can create a physical barrier and greatly reduce entry of pests into the greenhouse from outside (Figure 23).

Figure 23. Accordion-style exclusion screens covering roof peak vents.

These can include flying insects or other arthropod pests and plant pathogens blown in through vents by the wind. Additional benefits include fewer escaped biocontrol agents and pollinators and a reduction in environmental extremes. For example, vents covered by screens can be opened during wind or rain events which eliminates the risk of wind damage to the plants, while allowing for greater air flow during these weather events. In warmer climates where pests occur outside all year, screening is an established part of IPM programs. While not as common in temperate areas, **vent screening** is becoming more common and its value more apparent.

The most important considerations in screening a greenhouse are the type of pests being targeted for exclusion and how screens will affect greenhouse venting capacity.

The size of the pest determines the screen mesh size needed. For details on mesh sizes, see factsheet *Screening of Greenhouses for Insect Exclusion*[50] on ontario.ca and Optimizing Air Movement with Pepper Weevil Exclusion Screening[42]. The large mesh sizes common for household screens are too big to exclude most major greenhouse pests. However, they can be useful for keeping out occasional larger pests such as tarnished plant bug and lepidopteran (moth) pests. For smaller insects such as thrips, the mesh must be very fine to achieve total exclusion. When there are multiple pests of concern, choose a mesh
size that will exclude the smallest of the target species.

Reduction of airflow capacity is one of the principal concerns for producers considering screen installation. Reduced airflow can lead to the greenhouse overheating. In the case of fan-ventilated greenhouses, it also puts stress on the fans since they must work harder to pull the same amount of air through the partially blocked vent. Reduced ventilation can be addressed by increasing the total surface area of screened openings. Note that forced ventilation/wall vents are much easier and less expensive to screen than retrofitting top vents. The goal is to ensure that the final surface area of the screens provides sufficient air exchange to allow adequate greenhouse cooling.

Several factors determine how much extra vent surface area must be added to compensate for vent screens:

- screen mesh size
- fan capacity
- static pressure drop (difference in air pressure between the inside and outside of a greenhouse when fans are running)

Although software programs exist to help with optimizing venting set points and calculation of these parameters, they can be complex to compute manually and are best done by screening manufacturers.

Screens should be inspected and maintained after installation. It is important to:

- Clean screens regularly. They easily become blocked with dust and other deposits, reducing airflow further and may contribute to excessively high temperatures in the greenhouse. Wash screens from the inside with a high-pressure hose. Do not do this when the fans are operating. Ensure easy access for cleaning is incorporated in screen design.
- Repair tears or holes as soon as possible. The effectiveness of the screens depends on their ability to exclude flying insects.

Mass Trapping

The concept of mass trapping centres on using a high density of traps that attract a specific pest with the goal of reducing the size of its population. Examples of traps are:

- sticky traps (cards or tape, with or without pheromone baits)
- light traps
- attractive host plants (trap plants)
- combination of the above

Sticky traps

Applying yellow sticky tape, large sticky cards or a high density of small sticky cards in and around a crop can assist with management of flying insect pests (Figure 24A) and (Figure 24B). It works on the same principle as the sticky cards used for monitoring.

Figure 24. Mass trapping techniques. (A) Adult thrips caught on sticky card. (B) High density of sticky traps. (C) Yellow sticky tape along top of plants. (D) Yellow sticky tape near root zone. (E) Pheromone-baited large sticky trap barrier. (F) Scissor cart wrapped with sticky tape.

Focus on areas of the greenhouse where targeted pests will occur. Place the sticky traps along plant rows, hang them vertically within the crop or at common entry points like side vents or doorways. For example, if targeting adult whiteflies, place sticky tape near the top of the plant all the way down the row (Figure 24C). Alternatively, if targeting adult fungus gnats, sticky traps should be placed near the root zone (Figure 24D).

When available, pheromone-baited lures can be used to increase the quantity of pests attracted to sticky traps (Figure 24E).[26] Equipment such as scissor carts can be wrapped with sticky tape to catch whiteflies as employees move down each row (Figure 24F).

Light traps

Like the traps used for monitoring, light traps also reduce or suppress nocturnal moth pests through mass trapping them.

Trap Plants

As with monitoring, plants that are more attractive than the cultivated crop can be used to trap pest populations. These plants may be treated with pesticide or simply disposed of once pest populations are established.

D. Biological Management

One of the most successful strategies for management of pests in a greenhouse is application of biocontrol agents.[41] These natural enemies are living organisms such as beneficial insects, mites, fungi and bacteria that are selected to specifically manage problem pest species. **Beneficial microorganisms** (or microbes) are organisms such as fungi and bacteria that attack pests. Entomopathogens are beneficial nematodes, microbes or viruses that target insects.

Successful biocontrol programs often require advanced planning and preventative releases and should include the following considerations:

- Determine what specific pests should be targeted for management and which biocontrol agents are appropriate to apply to control it on the target crop (Appendix C).
- Develop a list of resources to help with developing the program. This may include talking to producers/suppliers of biocontrol agents, other growers, extension specialists, researchers and consultants.
- Attend courses, seminars and workshops, read articles and use digital tools to learn about biocontrol options.
- If possible, when testing new agents and strategies for supporting biocontrol programs, start in a small, isolated area of the greenhouse. Collect data to evaluate whether the strategy was successful and if so, expand the program to cover the entire greenhouse area, thus minimizing chances of economic failure.
- Ensure all employees are trained to recognize all stages of both the target pest and their biocontrol agents and early symptoms of pest damage.
- Optimize environmental conditions prior to biocontrol agent release to support their establishment in the crop. Note which biocontrol agents can be used preventatively (inoculative biocontrol) and which are used reactively (inundative biocontrol).

Be knowledgeable about compatibility of biocontrol agents with each other and with any pesticide being applied to crops. Many registered pesticides can have non-target impacts and residual effects. Check prior pesticide spray records over several months. If persistent pesticides have been used, wait the appropriate length of time before starting. Use products with less residual impact to manage pests during this period. Refer to supplier databases or the ministry's *Ontario Crop Protection Hub* for details.

Rates of application may differ based on the crop, environmental conditions and pest pressure.

Biological Control Agents (Biocontrols/BCAS)

There are four general categories of biocontrol agents: predators, parasites or parasitoids, beneficial nematodes and beneficial microbes and viruses.

Common characteristics of predators:

- usually larger than their prey
- fairly mobile and often move rapidly
- many are predatory as both immatures and adults
- eat and kill many prey as they grow and reproduce, otherwise live independently of them
- must consume more than one individual to reach maturity

Common characteristics of parasitoids:

- usually about the same size or smaller than their host
- all undergo complete metamorphosis
- eggs are laid on **(ectoparasite)** or in **(endoparasite)** the insect host
- usually require one individual host to complete development

Common characteristics of beneficial (entomopathogenic) nematodes:

- lethal to insects but safe for plants
- use symbiotic bacteria
- have a wide host range

Common characteristics of beneficial microbes and viruses:

- cause damage or a disease to the pest (could be targeting arthropods or plant pathogens)
- may induce resistance or promote plant growth
- specific conditions are necessary for optimum performance

Although beneficial microbes, also known as microbial biopesticides,[1] are considered biocontrol agents, they are regulated under the same legislation as **conventional pesticides** when claims are made that they control a plant pathogen. As well, since their application is similar, they are discussed further in the following section (E).

Biocontrol Agents

Biocontrol agents can be broadly grouped by whether they are a **specialist** or a **generalist**. A specialist typically feeds on one or a few related prey species, whereas a generalist may have multiple food sources including multiple diverse prey species and sometimes also plant derived foods such as pollen or nectar.

Some biocontrol agents may also kill and eat competitor beneficials from either the same species (cannibalism) or different species **(intraguild predation)**, particularly in the absence of adequate pest food. These instances can be mitigated by addition of **supplemental foods** such as pollen or inactivated flower moth eggs.

An interesting and poorly understood element of biocontrol is **parasitoid host-feeding:** when parasitoids act like predators, killing the target pest through direct feeding. Certain parasitoid species may kill target pests through host feeding at an even greater rate than through **parasitism**. For example, a large proportion of whitefly nymphs may be killed by the parasitoid *Eretmocerus eremicus* through host feeding.

Another one of the most interesting and difficult aspects of biocontrol to observe outside of a research setting are the **non-consumptive effects** these agents provide. The more obvious **consumptive effects** include killing and eating (consuming) their prey. Non-consumptive effects include:

- intimidation or harassment of their prey which results in reduced feeding
- predator avoidance
- fewer eggs laid
- stunted development
- increased susceptibility to **entomopathogenic** fungi[36],[78]

See *Biological control auxiliaries information sheets* by the *Centre De Recherche Agroalimentaire de Mirabel* for detailed information on application, compatibility of agents and environmental conditions necessary for successful establishment.

Approaches and Application Methods for Biocontrol

There are several different approaches to releasing arthropod biocontrol agents:

- classical
- augmentation
- conservation

With **classical (or importation)** releases, the target pest is usually an exotic invasive species and its natural enemies from the native range may be imported to manage them. This approach is not typically used for greenhouse production.

With **augmentative** releases, biocontrol agents are usually produced in insectaries. **Inoculative** releases occur when a biocontrol population establishes and expands on crops to adequately manage the pest population over time. **Inundative** releases are when large numbers of biocontrol agents are released to rapidly overwhelm the pest.

The **conservation** biocontrol approach includes reducing factors that interfere with the natural establishment of beneficial arthropods or providing these agents with necessary resources to promote growth of their populations.[22],[44],[66]

A combination of the three approaches could be used concurrently. For example, to manage two-spotted spider mites on greenhouse tomatoes, inoculative releases of *Phytoseiulus persimilis* would result in established populations in that crop. If a pesticide application was warranted, a bio-compatible product would be chosen to maintain populations of *P. persimilis*. This would be an example of augmentation and conservation.

In some cases, **banker plant systems** and food supplementation can also be used to support the establishment of biocontrol agents.

The banker plant system provides an alternate source of food or a place to reproduce.[44],[45],[66] For example, aphid banker plants contain aphid-infested cereal plants that promote aphid parasitoid development and population growth. Such cereal plants are typically inoculated with an aphid species that will not feed on or infest the primary crop grown in the greenhouse so there is not a risk of cross-contamination (Figure 25A). Another example is mullein plants, which may be utilized for supporting reproduction for the predator, *Dicyphus hesperus* (Figure 25B) or *Alyssum* species plants, that will be frequented by predators such as *Orius insidiosus* and several parasitoid species as a source of nectar (Figure 25C).

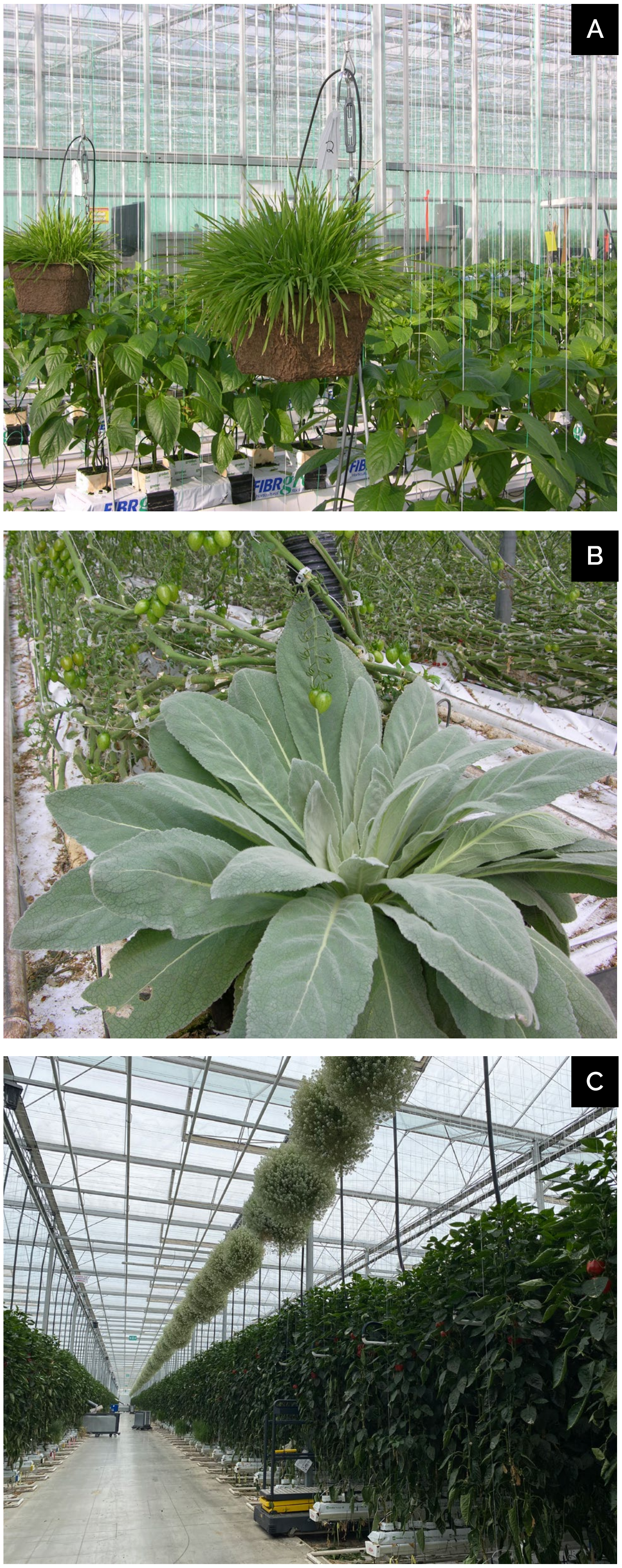

Figure 25. (A) Cereal banker plants for aphid parasitoid, *Aphidius colemani*. (B) Mullein banker plants for *Dicyphus hesperus* reproduction. (C) Alyssum banker plants for *Orius* species and parasitoid fitness.

Food supplementation involves providing natural enemies with a food source in addition to pest prey, that improves how long they remain on the crop and facilitates long-term and preventative establishment of many beneficials.[39] For example, *Ephestia* eggs, *Artemia* cysts or a combination of the two, can increase the establishment of the generalist predator, *Dicyphus hesperus*. However, *Orius insidiosus* prefers *Ephestia* eggs and pollen.[39]

The use of artificial lighting can have an impact on both pests and biocontrol agents. There may be benefits and drawbacks as it may support the establishment and use of some biocontrol agents, while supporting the population growth of certain pests. In either case, consideration should be given to the need to alter the biocontrol program to use a combination of biocontrol agents that will be successful in an environment with artificial lighting.

It is important to follow all instructions provided by suppliers for correctly storing and releasing biocontrol agents.

Storing Biocontrol Agents

Many agents can be stored only for a short period of time under specific conditions. These products should be labelled with specific storage conditions or the information can be obtained from suppliers.

General instructions for biocontrol handling and storage are:

- On arrival, the box should be cool, free of excessive moisture or foul smells such as ammonia or yeast.
- Bottles should be stored horizontally to minimize compression and maximize oxygen in the bottles.
- Temperature and humidity are important factors for storage. Most refrigerators are too cold to meet requirements for storage and it is sometimes best to use a cooler

with ice packs or leave them at room temperature. Alternatively, there are specialized coolers for purchase through suppliers.

- If storing a box of sachets in the greenhouse, leave the box open to avoid buildup of carbon dioxide. Keep sachets out of direct sunlight.

The quality of biocontrol agents produced by the major insectaries is usually excellent, but problems can occasionally arise during shipping. Quality assessments can be done on-site. Consider the methods used for these assessments to ensure they are done in a way that truly assesses product viability and vigour. Some assessment guides are available, but working with suppliers to ensure the methods are appropriate to the specific agent or product is recommended. Ideally biocontrol agents are released as soon after arrival as possible and directly into the greenhouse crop.

Releasing Biocontrol Agents

Release methods may vary for different products. Gently roll the bottle while on its side to mix the contents. DO NOT shake the bottle because it could damage the agents inside. Distribute biocontrol agents evenly throughout the crop or apply extra to hotspots.

Options for releasing wingless biocontrol agents like predatory mites are:

- Sprinkle loose product onto the foliage of infested plants.
- Manually broadcast by applying to the entire crop.
- Use blowers for vermiculite or bran-based products. Must be calibrated by checking for live, in-tact mites on the crop at different distances.
- Hang sachets directly on the stems and avoid leaves that may fall off or be removed. Place out of direct sunlight to optimize release rates.

Options for releasing flying biocontrol agents like parasitoids are:

- Sprinkle loose product onto the foliage.
- Release boxes with a thin layer of material to avoid product falling off the plant.
- Hang cards or sachets directly on the stems avoiding leaves that may fall off or be removed. Place out of direct sunlight to optimize release rates.

Steps After Releasing Biocontrol Agents

Monitor populations of pests and biocontrol agents. Evaluate progress of the biocontrol program by regularly checking for:

The presence of parasitized insects. For example, black pupae indicate that *Encarsia formosa* has parasitized whiteflies, while mummified aphids indicate that they have been parasitized by parasitic wasps such as *Aphidius* species.

The presence of wingless biocontrol agents. For example, observations of predatory mites and immature ladybeetles that do not fly requires visual inspection of the crop. Pay particular attention to areas of high pest numbers. Note signs of predator establishment and feeding, including different predator life stages or dead pests.

Pest population trends. Monitor pests either on sticky cards or the crop to determine if populations are increasing or decreasing.

If necessary, use pesticides. Begin with bio-compatible pesticides first to minimize harmful effects on biocontrol agents. Identify such pesticides before starting a program so they can be readily used when needed.

Effective release methods for predators and parasitoids in greenhouse crops on ONGreenhouseVegetables.ca provides more information.[76]

Commercially Available Arthropod and Nematode Biocontrol Agents

Commercially produced biocontrol agents are available for all major greenhouse insect and mite pests (Appendix C). For more details about implementing biocontrol programs or about supplies of parasitoids or predators, consult IPM specialists and biocontrol suppliers, see *Biological Control Agents Suppliers.*

Regulations of Biocontrol Agents

In Canada, the import, handling and release of biocontrol agents including insects, mites and nematodes is regulated under the *Plant Protection Act* through the Canadian Food Inspection Agency (CFIA). Regulations are intended to mitigate the unintended and potentially negative impacts of introduced species to non-target hosts in new environments. For more information regarding current regulations see *Import and release of biological control agents* on the *Canadian Food Inspection Agency* website.[13] Microbial biocontrol agents are regulated as biopesticides under the federal *Pest Control Products Act*[58] through the Pest Management Regulatory Agency (PMRA) of Health Canada. For more detailed information about Canadian regulations see *Biopesticides* on the *Agriculture and Agri-Food Canada* website.[1]

Non-Target Side Effects of Pesticides

Caution is required when using pesticides along with biocontrol agents since many pesticides are harmful to beneficial insects and mites. Additionally, some pesticides have a **residual activity** (sometimes referred to as persistence) that prevents the successful establishment of biocontrol agents for a specified period of time that lasts up to several months. Generally, pesticides are rated in terms of their impact on biocontrol agents as ranging from "soft" to "hard" based on their potential to incur mortality and their persistence. As a rule of thumb, choosing to first apply softer products that are effective against the target pest and reserving harder products as a last resort, can help preserve or extend existing biocontrol programs. For more information on non-target effects of **active ingredients (a.i.)** on specific biocontrol agents, see Compatibility Details at the ministry's *Ontario Crop Protection Hub.*

E. Biopesticides and Conventional Pesticides Management

Pesticides are a widely used pest management tool in commercial agricultural production systems. Their role varies from prevention by protecting healthy plants, to treating infected or infested plants. Pesticides contain one or more active ingredient, which are the components responsible for control of a pest. In the greenhouse, traditional pesticides include **insecticides** and **acaricides** that target insect and mite pests, respectively, as well as **fungicides** and **bactericides** that target fungi, oomycetes and bacteria. More recently, **vaccine-like pesticides** have been developed that target plant viruses, including mild or attenuated viruses.

There are two broad types of pesticides used in greenhouse production: conventional pesticides and biopesticides. Both conventional and biopesticides must be registered by the PMRA before commercial availability in Canada.

Conventional pesticides are usually made of synthetic chemicals or have synthetic components. Biopesticides are chemicals derived from natural sources such as bacteria, fungi, plants, animals and minerals.

There are three different types of biopesticides in Canada:[1]

- microbial
- **semiochemicals**
- **non-conventional pest control products**

Microbial pesticides include pathogens or parasites, competitors or inducers of plant host resistance. Some beneficial microorganisms strongly suppress plant pathogens and arthropod pests without harming the crop.

Mechanisms of action are:

- competition
- **antibiosis**
- parasitism
- induced resistance

Like other biocontrol agents, each microbial biopesticide product may have specific storage and handling requirements. Be sure to follow guidelines on the package. Many require refrigeration and can be stored until the best before date.

Semiochemicals are message-bearing chemicals produced by an organism that cause a behavioural response in another organism of the same (intraspecific) or of a different species (interspecific). There are different types of semiochemicals, but synthetically produced insect sex pheromones are those most used in IPM programs for monitoring, trapping and mating disruption.

Non-conventional pest control products are those that inhibit growth, feeding, development or reproduction. For example, plant or microbial extracts and mineral oils.

Many biopesticides are most effective when used preventatively or used early in the crop cycle and with regular applications.

Some products and formulations meet organic certification requirements, meaning they may be approved for use by the governing body for organic producers.

Resistance Management

Different pesticides work to manage pests in different ways depending on their molecular structures and how these interact with the cellular target sites. Pesticides can thus be categorized based on their modes and sites of action of the active ingredient(s). The **mode of action** is “how” the pesticide works. Whereas the **site of action** is “where” the pesticide works.

The Insecticide Resistance Action Committee (IRAC)[34] and Fungicide Resistance Action Committee (FRAC)[27] working groups classify pesticide groups into families/groups according to their mode of action. These groups can be further divided into subgroups of pesticides with similar modes of action (for example 20A, 20B, etc.). Information on IRAC and FRAC classifications can be found on their websites. Being aware of these groups is important as using pesticides with the same mode of action repeatedly (year after year or several times within the same crop cycle), increases the likelihood of resistance development. Resistance can develop in either the target or even some non-target pest species. And yet, while a pest can develop resistance to one chemical family, it can still be very susceptible to another.

The development of resistance in pest populations is an important driver for adoption of IPM. **Pesticide resistance** occurs when there is a heritable (transmitted from one generation to the next) change in the sensitivity of a pest population to a particular active ingredient. This is evidenced by repeated failures of a pest control product to achieve the expected level of control. While an individual cannot develop resistance during its lifetime, the presence of one or a few individuals in a population may carry a heritable resistance trait that will be heavily selected for in the next generation, especially with repeated exposure to the same class of chemical pesticide. Thus, the frequency of resistance in a population will inevitably increase when pesticide exposure kills susceptible individuals, allowing successively greater numbers of resistant individuals to survive (Figure 26). Because of the immense genetic diversity of many pests, their short life cycles, their great reproductive ability and the relatively isolated and protective nature of greenhouse production, greenhouse pests have considerable potential to develop resistance. Relying on pesticides inevitably leads to the development of resistant populations.

There are different types of pesticide resistance including **cross-resistance** and **multiple resistance**. Cross-resistance occurs when a pest is resistant to different subgroups that have a similar mode of action. Multiple resistance is when a pest is resistant to different groups with different modes of action. Cross-resistance is more common than multiple resistance.

Resistance management programs aim to reduce the pressure that pesticides apply to pest populations. The best approach is to minimize the use of pesticides by considering them strictly as a last resort. This can be done by setting a priority in pest management to apply preventative biocontrol and reapply as

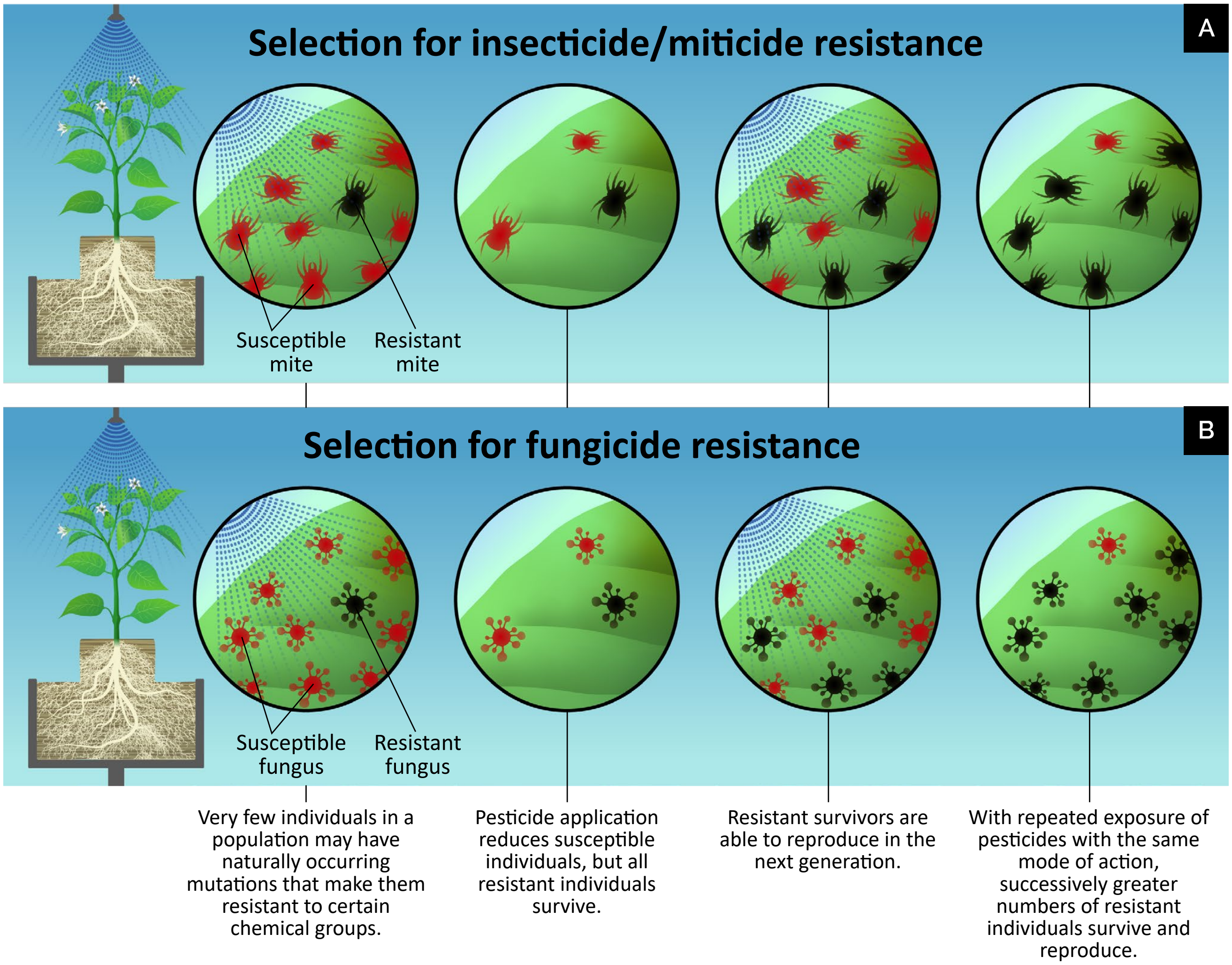

Figure 26. (A) Selection for insecticide resistance. (B) Selection for fungicide resistance.

needed, implement key physical and cultural management tactics and use preventative bio-compatible pesticides as needed. As a last resort, judiciously and sometimes selectively apply conventional pesticides when necessary. Although pests can still develop resistance to some biopesticides, they are generally considered lower risk and many can be used preventatively. Alternating between chemical groups remains a viable strategy for resistance management and highlights the importance of understanding active ingredient classes as they relate to their target sites or modes of action.

To reduce the risk of pest resistance development, apply the following strategies:

- Avoid repeated application of pesticides from the same chemical group or subgroups (indicated by the IRAC and FRAC Mode of Action Group number) by rotating between chemical groups with different modes of action.
- For pests with distinct generations, use products within one mode of action group only for the duration of one generation of the target pest before switching to another group for the following generation.
- For pests with overlapping generations (like aphids or mites), use an appropriate window of application that accounts for the duration of its generation or a stage of crop development. For example, IRAC recommends a 15-day window for aphids and mites and a 30-day window for most other pests.
- Use low risk fungicides (such as biofungicides within the BM01 or BM02 FRAC groups) in rotation or combination with medium and high-risk fungicides when possible.
- Only use pesticides when necessary and integrate them as much as possible with other management strategies in an IPM program.
- Follow all label recommendations. Do not exceed the total number of applications allowed per year or per crop cycle for each product. Do not apply the product at rates lower than the recommended rate on the label as exposure to low doses can increase resistance development as well.
- Monitor recently treated pest populations for signs of resistance (for example lower reductions than expected based on claims on the label).
- Read the pesticide label for more information on resistance management.

For more information on pesticide resistance management strategies, see IRAC training modules available at the *IRAC Training Centre* and *Fungicide Resistance Management* recommendations at the FRAC website or visit the ministry's *Ontario Crop Protection Hub.*

Pesticide Application Methods, Movement and Efficacy

Depending on what is specified on the label, pesticides can be applied in different ways being either foliar, drench, fog and sometimes vectored via pollinators (Table 2).[18]

Table 2. List of Application Techniques, Targets and Relative Water Volumes

Application Technique	How	Target	Water Volume
Foliar	spray equipment	leaves, stems or fruit	moderate
Drench (sometimes called drip or chemigation)	through the irrigation system or by hand	root zone	relatively high
Fog or vapour	convert solution to vapour	large volumes of the greenhouse	low
Pollinator (sometimes called apivectoring)	bumble bees used to disseminate microbial biopesticides	often flowers but sometimes leaves, stems or fruit	none

Apart from these methods, there are also some pesticides available in granular formulations that can be applied directly to the growing medium.

Movement or lack of movement of pesticides on or within crop plants differs between active ingredients.[38] Pesticides vary by how they:

A. interact with the plant (remaining on the surface or moving into tissues)
B. reach the target pest (through contact, ingestion or inhalation)

A. Interaction With the Plant

Contact or surface-bound pesticides have limited plant-penetrative attributes. Some have very little penetrative potential and remain on the surface through adsorption only (adherence). Others can penetrate the plant cuticle (absorbed), are less resistant to wash-off and may have long residual activity. Contact pesticides must cover plant surface(s) where pests are active and likely to come into direct contact with the residue. Ideally, a high density of uniform deposits that do not incur runoff improve the efficacy of these products.

Translaminar pesticides penetrate plant tissues and form a reservoir of active ingredient near the point of application or in other words, they are locally systemic. When applied as a foliar spray, translaminar pesticides can move from the top surface of a leaf to the underside, resulting in protection against pests like aphids. Local redistribution in surface tissues by expanding beyond the pesticide deposit, improves coverage relative to surface-bound materials. The degree of coverage required is not as stringent as that of a contact product but should be more than a true systemic.

Systemic pesticides can move within the plant's vascular system increasing the degree of protection beyond the area covered by the initial deposit. Systemic pesticides are taken up passively or actively by the roots or are absorbed/adsorbed by foliar tissues. It might take some time before the active ingredient moves to all plant parts including new growth. Most systemic pesticides tend to move upwards (with water in the xylem) rather than downwards (with sugars and nutrients in the phloem) so foliar applications should be targeting at or below pest populations. Applications absorbed by the roots tend to provide much longer residual activity compared with foliar applications. In either case, residual activity can vary from 2 to 12 weeks. Depending on the size of the plant and application rates there may be little active ingredient that ends up in the new growth at the top of the plant.

B. Reaching the Target Pest

Contact pesticides kill pests when they come into direct contact with residues of the active ingredient. This occurs when the pests walk on treated surfaces or through **ovicidal** effects, when eggs are laid on or under treated surfaces. Pesticides that reach the target through contact are typically surface-bound materials, although systemic or translaminar products may kill on contact if the active ingredients have not yet been absorbed by plant tissues. Good coverage, especially relative to where pests are active, directly impacts efficacy of these products.

For arthropod pests, pesticides that work through **ingestion** must be deposited on plant surfaces that pests are likely to consume to have a toxic effect. Feeding on plant tissues containing active ingredients, whether they are surface-bound, translaminar or systemic, exposes the target pest to the pesticide. Some insecticides have **ovi-larvicidal** effects, killing emerging larvae as they chew through the egg **chorion**. Uniform deposition is always preferable, but the percent of the target surface requiring coverage depends on the nature of the pesticide. In cases where the deposit attracts pests or is capable of secondary movement due to spreading or plant uptake, less surface need be covered and vice versa.

Pesticide efficacy is a measure of the performance of the product expressed as partial suppression, suppression or control potential.[59] This could be measured by mortality of the pest or negative impacts on their ability to feed and reproduce or reductions in damage to the crop. It is important that the product provides consistent results with the lowest effective rate without unacceptable injury (phytotoxicity) to the crop.

The performance claims for control of arthropod pests are not rigid thresholds but require data to demonstrate that the reduction in numbers of pests or damage is commercially acceptable. Suppression of arthropod pests claims may mean the performance is less consistent but still has value in an IPM program when combined with other strategies or if they provide other benefits. For example, the product may have a different mode of action which makes it suitable for rotation or the product may have minimal non-target effects.

For fungicides, these performance claims mean different things. Control of plant pathogens may be achieved by reducing disease incidence or maintaining yield potential, depending on the target pathogen species. While suppression of plant pathogens may still offer commercially beneficial consistent control that is not optimal.

If the product is not achieving expected levels of performance on farm, other factors may be affecting the experienced efficacy. Factors affecting efficacy include application technology, technique, timing, coverage, temperature, light, moisture, pH, resistant pest populations, etc. For details see Table 3.

Pesticide Application Technology

The type of application technology (equipment) used in greenhouse production varies. Basically, spray equipment meters a liquid solution (often in the form of droplets) and conveys it to the target. Most often, the target is described as the pest population.

Table 3. Measures to Maximize Effectiveness of Pesticides

Factor	Recommendation Measures
Accuracy	Ensure the pesticide application rates are accurately calculated and measured.
Coverage	Ensure proper coverage is achieved at the target site (e.g., targeting a pest on the fruit vs leaves). Simple changes, such as moving more slowly through the crop and maintaining a consistent distance between the spray nozzle and the target, significantly improve performance.
Maintenance	Maintain spray equipment. Certain chemistries can corrode and damage application equipment and components will require both maintenance and/or replacement with use. A regime of regular cleaning and maintenance per the manufacturer’s guidelines will ensure optimal performance and reduced downtime.
Application Technology	Consider different application technologies. Application equipment is designed with purpose and may not be suited to every need. The distance from the point of atomization and the target, the volume of carrier and the size and density of the target canopy will dictate the best tool for the job. Ensure the equipment used is appropriate for the pesticide and the purpose.
Timing	Time and target sprays for greatest impact. A scouting program can provide the information required to decide when, where and why a pesticide application is needed.
pH	Adjust water pH to 5.5–6.0. At a pH greater than 7, the pesticide may degrade rapidly.
History	Keep in mind the usage history of a particular product within the greenhouse and rotate chemical groups.

In some cases, the target might include a specific part of the plant to facilitate the movement of the pesticide to the pest. For example, a drench application of a systemic insecticide targeting a foliar-feeding insect is relying on the roots to take up the insecticide and translocate it to the part of the plant where the insect is feeding. Each piece of equipment may differ in the amount of water it uses, operating pressure, droplet size and the labour required to operate it (Table 4). The degree of coverage required is sometimes indicated on the pesticide label.

Depending on the method, (foliar, drench, vapour), the choice of application technology depends on several variables.

Table 4. Important Considerations for Pesticide Application

Factor	Details
Droplet size	Ranges from Extremely Fine (approximately ≤50 microns (μm) in diameter) to Ultra-Coarse (approximately ›622 microns in diameter).
High volume of water/solution	These applications are performed at pressures ranging from 500 to 4,285 kPa (75 to 700 psi) employing flow rates of 3.9 to 5.7 L/min (1 to 1.5 US g/min). They use standard label rates to accomplish a dilute application by broadcasting droplets larger than 100 microns.
Low volume of water/solution	These applications are performed at high pressures around 20,685 kPa (3,000 psi) employing flow rates approaching 1 L/min (0.26 US g/min), covering 93 m^2 (1,000 ft^2). They apply reduced rates over a given area and create droplets between 25 and 100 microns.
Ultra-low volume (foggers) of water/solution	These applications employ flow rates approaching 2 L/min (0.52 US g/min), covering 930 m^2 (10,000 ft^2). They require concentrated solutions but apply reduced rates per area using droplets less than 25 microns.
Calibration	According to the operator and crop.
Pressure	Affects the application rate and spray distribution. Usually measured with a gauge indicating pressure at the nozzle. See volume.
Coverage	Uniform distribution of the active ingredient over the desired target. This can be evaluated using water sensitive paper (Figure 27). Note that high humidity and free water on the plants can affect the observations of the paper if left in the canopy for too long.
Application efficiency	Efficiency means you prevent the wasteful use of resources such as time, money or pesticide. Wasted product refers to any spray liquid not deposited on the target (for example, drift, run-off, leaks, spills, left-over spray mix).
Application efficacy	Efficacy means you are successful in producing the desired outcome. For example, if a pesticide is labelled for suppression and suppression was achieved, then the application was effective.
Nozzles	A conventional hydraulic nozzle meters the flow of bulk spray liquid, converts it into a range of droplet sizes and disperses them in a specific geometric shape; all in response to hydraulic pressure. Examples include flat fan, hollow cone or dual flat fan (Figure 28).

Figure 27. Under-leaf coverage with a manually towed sprayer using TeeJet VisiFlo hollow cones (TX-VK3) operating at >300 psi.
Source: sprayers101.com, *Photo*: Jason Deveau

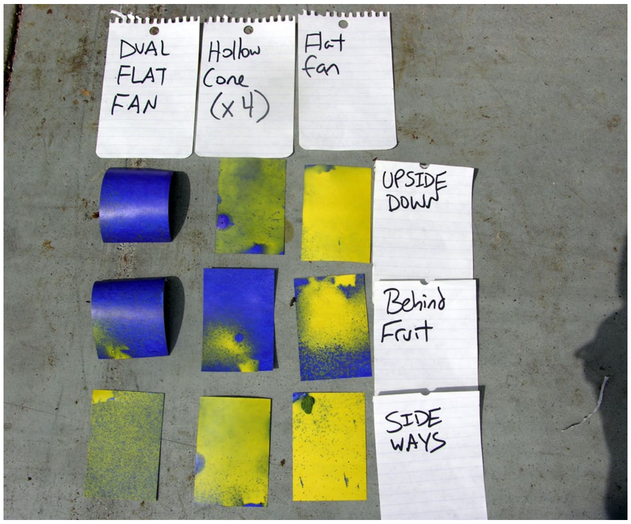

Figure 28. Coverage from three sets of nozzles. Papers oriented in three different ways in a greenhouse tomato vine using an automated vertical boom.
Source: sprayers101.com, *Photo*: Jason Deveau

Pesticide application equipment includes high-volume hydraulic sprayers, low-volume sprayers or ultra-low volume sprayers (including foggers). Some labels allow for applications through irrigation systems or using a burner and some include the pollinator-application method. Ideally, each combination of canopy morphology, planting architecture, pest and chemistry would have a specific sprayer designed to optimize coverage and efficiency. This is economically unrealistic. Instead, many producers utilize technologies that rely on high water volumes and hydraulic pressures to "drench" targets indiscriminately. Others employ highly manual methods that allow the operator to aim the nozzle in relation to the canopy on a case-by-case basis, but still rely solely on water to distribute the insecticide.

Many greenhouses use more than one application technology to assist with a wide range of needs. Applicators should use appropriate PPE based on technology used and specifications on pesticide labels. Below are descriptions of some technologies commonly used in greenhouse fruit and vegetable production.

High-Volume Hydraulic Sprayers

With high-volume or hydraulic sprayers, the energy is generated through a pump that creates pressure to get the solution (active ingredient plus water) to the target (the plant). These sprayers are most often used for contact pesticides and use large volumes of water allowing foliage to be sprayed to wet/point of runoff. Different nozzle choices dictate the size of the droplets (usually between 200-400 microns) and the direction of the spray solution.

Backpack Sprayers

This method is often used for spot-spraying and is usually operated using a hand pump that pressurizers the solution and a wand with nozzles directing the spray to its target.

Manual Sprayers

These sprayers have a manually towed vertical boom with a coil of hose, where the operator would tow the sprayer between the rows at a constant speed (Figure 29). There is a centralized tank and pump, located outside the growing area. Products are mixed and pumped from there. The pressure is set at the source and some operations experience a significant pressure-drop at the far reaches of the greenhouse. Sometimes the pressure can be controlled with a regulator on the boom.

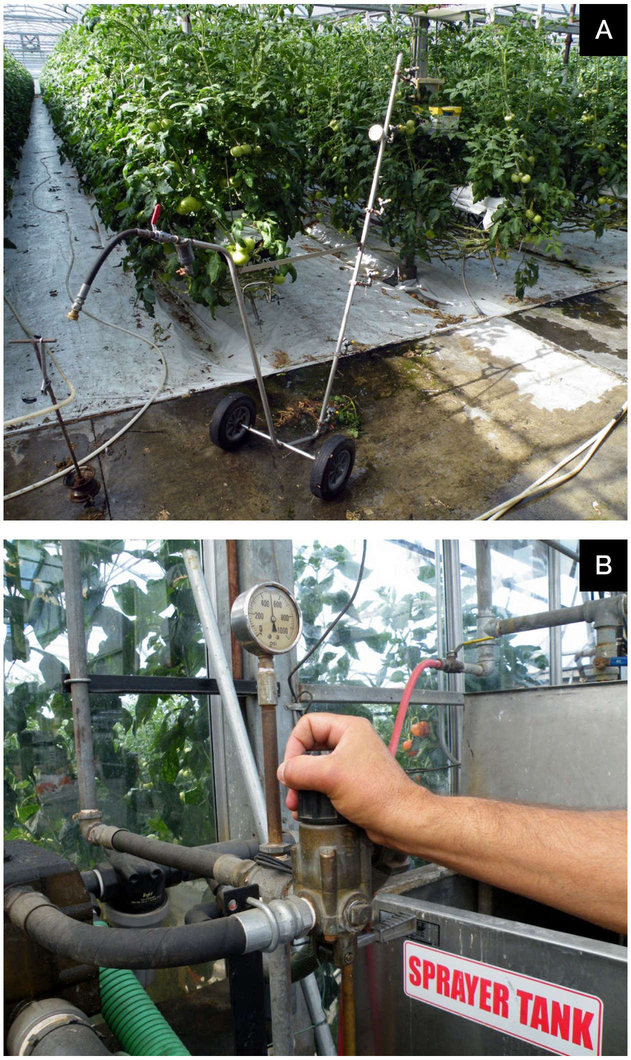

Figure 29. (A) Manually towed vertical boom. (B) Pressure regulator.
Source: sprayers101.com, *Photo*: Jason Deveau

Automated Vertical Boom Sprayer (Spray Tree)

Robotic (automated) vertical booms can ride along the pipes between rows (Figure 30). The operator generally stands in the corridor and sends the sprayer down the row.

Use caution when calibrating or adjusting the sprayer depending on your goal which could be to improve coverage or reduce waste.

When calibrating sprayers to improve spray coverage, remember to reconsider how much spray is needed to accomplish these goals.

Figure 30. Automated vertical boom sprayer.

Low-Volume Sprayers

These sprayers use more concentrated pesticides (less water than high-volume sprayers) to deliver pesticides to the target. Using high pressure between 1,000 and 3,000 psi, the pesticide solution is injected into an air stream using a fan, blower or compressor, to create finer droplets (usually between 50-100 microns).

Air-Assisted Sprayers use air to carry the product to the target, rather than rely on hydraulic energy. The reliance on hydraulic pressure and carrier volume has drawbacks:

- High water volumes lead to higher humidity in closed environments which may favour disease.
- The inevitable run-off creates wastewater that may require treatment before leaving closed environments.
- High carrier volumes dilute an already “soft” chemistry and hydraulic pressure doesn’t always improve canopy penetration or coverage uniformity.

Air-assisted spraying can be a viable alternative (and an improvement) over these approaches. Stationary or mobile, many low volume (and ultra-low) sprayers employ air to capitalize on the mechanical advantage offered by smaller and more numerous droplets. Finer droplets have very little mass, so they must be directed and carried by air currents to get them to the target. Sufficient air energy will also displace the air within the target canopy and physically expose otherwise hidden plant surfaces to the spray. Air can partially replace water as a carrier and it has the potential to improve coverage uniformity throughout the target canopy.

With electrostatic sprayers, spray is charged by a high voltage supercharger. Commonly, the charge is induced by an electrode positioned close to the atomizing spray plume as droplets begin to form. This is referred to as coronal discharge. An intense electric field imparts a positive or negative charge depending on the polarity of the direct current (DC) power used. Think of it as high-voltage static electricity. Sometimes the spray is atomized by a hydraulic nozzle (e.g., a hollow cone) and sometimes using an air-shear nozzle. The latter has the added advantage of blowing droplets away from the electrode and projecting them into the canopy.

Droplet size is a critical factor. Droplets must be large enough to resist evaporation and drift but small enough that the charge can change their trajectory when it comes close to a target (i.e., the **charge-to-mass ratio**). Most electrostatic nozzles produce approximately 50 microns droplets, categorized in agriculture as Very Fine. For comparison, a human hair ranges from 20–180 microns. Fog is about 5 microns. Such a small droplet means that the distance between nozzle and canopy is a determining factor for the spray depositing or drifting.

Ultra-Low Volume Sprayers

These systems, often called foggers, produce even smaller droplets (0.5–50 microns).

Stationary foggers rely on air circulation in the greenhouse to reach their target. Water sensitive paper has limited utility when evaluating coverage from foggers because droplets are extremely small (droplets of <50 microns are not reliably detected without **coalescence**). These systems may or may not require an applicator and are often used during hours when most employees are not present. Sufficient humidity is important to avoid evaporation of the droplets before reaching the target.

Mechanical foggers also called cold foggers, use high-pressure pumps and atomizing nozzles that deliver ultra-fine droplets to the target using an external fan (Figure 31).

Thermal foggers use extreme heat and an air stream to turn the pesticide into a vapour. These ultra-fine droplets can move long distances under the right conditions and can treat large areas in a short amount of time.

Figure 31. Mechanical fogger.
Source: Dramm Corporation. *Photo:* Louis Damm,

Drip-Irrigation

With these systems, sometimes referred to as drench applications, the pesticide is applied to the growing medium through irrigation channels. Where possible based on the location of the target pest population or systemic activity, this remains a desirable technique.

Pollinator Application

With these systems, dispensers containing active ingredient (likely the powder of a microbial biopesticide) are placed near the exit of the colony's hive. Bumble bees walk through the dispenser and deposit the microbial agent to flowers they are foraging.[18] They also drop inoculum onto crop foliage as they forage between crop flowers.

For more information on application technology see *www.sprayers101.com.*

Using Pesticides In Ontario

Regulation of Pesticides

Before a pesticide (pest control product) can be sold or used in Ontario, it must be registered under the federal *Pest Control Products Act* (PCP Act) and be classified under the provincial *Pesticides Act*.

A Pesticide Label is a Legal Document

Pesticide labels provide specific information on how to use a product safely, its hazards, restrictions on use, compatibility with other products, the effect of environmental conditions on its efficacy, etc. Consult each product label before using a pesticide. Ensure you have the most current label and are aware of any re-evaluation decisions. Emergency registrations are temporary registrations (1 year or less) for pesticides needed by growers to manage a new invasive pest or pest outbreak. Know the expiration date for pesticides you are using under an emergency registration. For more information on registered pesticides for use in greenhouses in Canada see the ministry's *Ontario Crop Protection Hub*.

For more details and information about label information (including restricted entry intervals and preharvest intervals), regulations, safety, training and certification *Using Pesticides in Ontario* on the *Ontario Crop Protection Hub*.

Success Criteria

IPM programs play a huge role in the success of greenhouse fruit and vegetable production in Ontario. To evaluate the success of IPM programs, producers should:

- Emphasize prevention rather than cure.
- Monitor crops at least weekly and educate and enlist employees in the early detection of pests or unusual symptoms.
- Keep detailed records using a system that can merge IPM strategies and pest data to analyze trends.
- Include other parameters to help anticipate potential pest problems. For example, a cool, cloudy and wet summer without proper climate management (heating and venting to manage RH) creates ideal conditions for many diseases such as downy mildew, late blight, gummy stem blight, Botrytis grey mould, etc.
- Correctly diagnose diseases and identify arthropods to determine how to manage the pest effectively.
- Develop a thorough understanding of the pests that commonly affect the crops being grown. Correct use and timing of management strategies then become part of an ongoing process.
- Develop a thorough understanding of the biocontrol agents used to manage pests. Provide an optimal environment conducive to biocontrol establishment and reproductive success through the crop cycle.
- Because pathogens are microscopic, learn to anticipate when pathogen infection periods are likely to occur. By the time the problem is visible, the pathogen has usually been present for some time and is more difficult to control.

Glossary

Above-substrate environment — refers to the environment outside of the growing medium where shoots, leaves, flowers and fruits are produced and includes light levels, temperature, air-movement, relative humidity and air quality.

Acaricide (also known as miticide) — any toxic substance (pesticide) that is used to kill mites.[8]

Action Threshold (AT) (also known as Economic Threshold/ET) — a level of damage or a pest population that triggers a management action in an integrated pest management program, thereby avoiding economic injury.[56],[57],[60]

Active ingredient (a.i.) — a component of a pest control product to which the intended effects of the product are attributed and includes a synergist but does not include a solvent, diluent, emulsifier or other component that is not primarily responsible for those effects.[58]

Antenna (plural = antennae) — slender, movable, segmented sensory organs on the head of insects.[43]

Antibiosis — antagonistic association between organisms to the detriment of one of them or between one organism and a metabolic product of another.[43]

Arthropod — any of a phylum (Arthropoda) of invertebrate animals (such as insects and arachnids) that have a segmented body and jointed appendages, a usually chitinous exoskeleton molted at intervals and a dorsal anterior brain connected to a ventral chain of ganglia.[43]

Ascospores — sexually produced spores within an ascus (saclike structure produced by fungi in the phylum Ascomycota; plural = asci).[8]

Augmentative biocontrol — rearing and release of biological control agents that are already present (or native) to increase their effectiveness.[60]

Bacterium (plural = bacteria) — any of a domain (Bacteria) of chiefly round, spiral or rod-shaped single-celled prokaryotic microorganisms that typically live in soil, water, organic matter or the bodies of plants and animals, that make their own food especially from sunlight or are saprophytic or parasitic, are often motile by means of flagella, reproduce especially by binary fission and include many important pathogens.[43]

Bactericide — any toxic substance (pesticide) that kills or inhibits the growth of bacteria.[8]

Bacteriophage — any group of viruses that infect bacteria.[8]

Baculovirus — any of a family (Baculoviridae) of DNA viruses that consist of one or more enveloped nucleocapsids, that infect arthropods and especially insects and that have been used as biological control agents for insect pests and experimentally in recombinant DNA technology as vectors for the expression of eukaryotic genes.[43]

Banker plant system — the use of specific plants within the crop environment that provide habitat and alternate food (prey or hosts) that are nonthreatening for the crop but support production of natural enemies (biocontrol).[45]

Basidiospores — sexually produced spores within a basidium (club-shaped spore-bearing organ produced by fungi in the phylum Basidiomycota).[8]

Beneficial microorganisms (also known as microbial biological control) — microorganisms that can be used to reduce damage by pests to tolerable levels;[49],[60] some may be naturally occurring and some registered as biopesticides.

Biofilm — aggregate of bacteria held together by a mucuslike matrix of carbohydrate that adheres to a surface.[8]

Biological control agents (also known as biocontrol) — living organisms used to reduce damage by pests to tolerable levels.[60]

Biological fix (also known as biofix) — the starting point for degree day accumulations based on either a biological event, such as the date of the beginning of moth flight or a calendar date, such as April 1.[72]

Biopesticide — pest management agents and chemicals derived from natural sources such as bacteria, fungi, viruses, plants, animals and minerals.[1]

Biosecurity — a set of practices used to prevent, minimize and manage the transmission of pests including their introduction, spread and release.[12]

Causal agent (also known as causal organism) — the organism responsible for causing disease in plants.

Charge-to-mass ratio — the charge of an object divided by the mass of the same object. For electrostatic sprayers, droplets must be large enough to resist evaporation but small enough that the attractive force of the charge can change the droplet's trajectory when it comes close to the target.[20]

Chasmothecium (plural = chasmothecia) — the fruiting body that contains asci.[30]

Chelicerae — one of the anterior pair of appendages of an arachnid often specialized as fangs.[43]

Chitin — a high-molecular-weight polysaccharide containing amino groups making up the bulk of an arthropods cuticle.[8]

Chlorosis — a diseased condition in green plants marked by yellowing or blanching.[43]

Chorion — eggshell of an insect, commonly provided with an air-filled meshwork providing respiration of the developing embryo.[8]

Classical biocontrol (also known as importation biological control) — biological control agents from the native range of an exotic invasive pest species that are imported and released to manage them.[60]

Coalescence — to grow together.[43]

Colony — a distinguishable localized population of a species or type of organism, a circumscribed mass of microorganisms usually growing in or on a solid medium.[43]

Compound eyes — an eye (as of an insect) made up of many separate visual units.[43]

Conidia — an asexual spore produced on a conidiophore of certain fungi.[43]

Conservation biocontrol — an approach that includes reducing factors that interfere with the natural establishment of beneficial arthropods or providing these agents with necessary resources to promote growth of their populations.[24],[60]

Consumptive effects — when biological control agents kill and eat their prey.[36],[78]

Contact pesticide — is adsorbed, susceptible to being washed off and does not protect plant parts that grow after the application; pests must come in direct contact with residues of the active ingredient.[6]

Controlled environment agriculture — advanced and intensive hydroponically-based agriculture where the crop is grown within a controlled environment to optimize plant health and production.[19]

Conventional (or traditional) pesticide — refers to a pesticide that is man-made or with synthetic ingredients (not biopesticides).[28]

Cross-resistance — resistance to two or more insecticides via a single mechanism of resistance.[34]

Cuticle — the outer layer or part of an organism that comes in contact with the environment. In many invertebrates the dead, noncellular cuticle is secreted by the epidermis. This layer may, as in the arthropods, contain pigments and chitin.[8]

Degree day (DD) — a unit that represents one degree of difference from a given point (such as 10°C) in the mean daily outdoor temperature and that is used especially to measure heat requirements.[43]

Defoliation — loss or shedding of leaves;[54] with insects often refers to feeding damage.

Diapause — in arthropods this a period of physiologically enforced dormancy with reduced metabolic activity between periods of activity. It may be triggered by unfavourable environmental conditions (such as winter) or is a necessary stage of their life cycle.[8]

Disease cycle — a series of events over a period of time that results in disease development.[35]

Economic Injury Level (EIL) — a measure of a pest population that causes economic damage.[57],[60]

Economic Threshold (ET) — see Action Threshold (AT).

Ectoparasite — a parasite that lives on the exterior of its host.[8]

Electrical conductivity (EC) — a measure of the total amount of salts, including fertilizer salts, in the growing medium.[74]

Endoparasite — a parasite that lives within its host.[8]

Entomopathogen — a pathogen that infects insects.

Epidermis — a thin surface layer of tissue in higher plants formed by growth of a primary meristem.[43]

Eukaryote — any cell or organism that possesses a clearly defined nucleus.[8]

Exclusion screening — a physical management strategy that uses mesh screens to cover vents preventing pests from flying or blowing in with wind events.

Exoskeleton — rigid or articulated envelope that supports and protects the soft tissues of certain animals. In arthropods, is formed from the epidermis and is composed of an outer waxy, water-resistant layer over chitinous horny and flexible layers.[8]

Flagellum (plural = flagella) — any of various elongated threadlike appendages that is the primary organ of motion of many microorganisms.[43]

Flagging tape — ribbon used to mark locations or plants within a greenhouse that are infested with pests.

Foliar diseases — diseases that infect above-substrate parts of the plants.

Food supplementation (or supplemental food) — the use of plant or alternate prey resources to improve establishment of biocontrol agents on the cultivated crop.[39]

Foregut — the anterior portion of the alimentary canal of insects that contains the pharynx, esophagus, crop and proventriculus and aids with ingestion and storage of food.[16]

Frass — the excrement of larvae; also, the refuse left behind by boring insects.[43]

Fungicide — any toxic substance (pesticide) that is used to kill or inhibit the growth of fungi.[8]

Fungus (plural = fungi) — any of a kingdom (Fungi) of saprophytic and parasitic spore-producing eukaryotic typically filamentous organisms formerly classified as plants that lack chlorophyll and include moulds, rusts, mildews, smuts, mushrooms and yeasts.[43]

Generalist predator — predator that feeds on several or many different species of prey.[60]

Genetic sequencing (also known as DNA sequencing) — technique used to determine the nucleotide sequence of DNA (deoxyribonucleic acid).[8]

Genus (plural = genera) — a category of biological classification ranking between the family and the species, comprising structurally or phylogenetically.[43]

Gnathosoma — an anterior region of mites that contains the mouth, specialized feeding appendages (chelicerae) and segmented structures called palps or pedipalps.[8]

Gram-negative bacterium — any of the various types of bacteria that are characterized by having a thin peptidoglycan cell wall surrounded by an outer membrane containing lipopolysaccharide that is in turn enveloped by a capsule. These bacteria are so-named because of their reaction to the Gram stain, where they characteristically stain pink or red following the Gram reaction, owing to their thin cell walls.[8]

Gram-positive bacterium — any of various types of bacteria that are characterized by having a thick peptidoglycan cell wall and by the absence of an outer membrane composed of lipopolysaccharide. These bacteria are so-named because of their reaction to the Gram stain, where they characteristically stain purple following the Gram reaction, owing to their thick cell walls.[8]

Gram's staining reaction — a microbiological staining technique that is used to identify and characterize bacteria.[8]

Growing medium environment — the environment within the substrate in which the roots grow including temperature, pH, nutrient levels, electrical conductivity, moisture-holding capacity, drainage and oxygen content.

Haustorium (plural = haustoria) — a nutrient-absorbing outgrowth of a fungus such as powdery mildew that penetrates the tissues of the host plant.[43]

Hemipterans — any of a large order (Hemiptera) of hemimetabolous insects (such as the true bugs) that have hemelytra and mouthparts adapted to piercing and sucking.[43]

Hemolymph — the circulatory fluid of various invertebrate animals such as arthropods that is functionally comparable to the blood and lymph of vertebrates.[43]

Heritable — naturally transmissible or transmitted from parent to offspring.[54]

Hindgut — is the posterior portion of the alimentary canal in insects that contains the pylorus, ileum and rectum and is responsible for mixing food residue and secretions from the midgut and assisting in eventual elimination of undigested material.[16]

Hyphae — one of the threads that make up the mycelium of a fungus, increase by apical growth and are transversely septate or nonseptate.[43]

Idiosoma — body cavity of mites that contains various organ systems bathed in hemolymph (arthropod blood).

Immunoassay test strips (also known as rapid test) — commercially available test kits using antibodies to detect the presence of specific plant pathogens on site.[54]

Ingestion — in pesticides where the pest needs to consume the active ingredient for it to be effective.

Inoculative biocontrol releases — involves periodic releases of biological control agents that establish and develop on crops to adequately manage the pest population over time.[60]

Inundative biocontrol releases — involves releases of high numbers of biological control agents to rapidly overwhelm the pest with no expectation of long-term pest suppression.[60]

Insecticide — any toxic substance (pesticide) that is used to kill insects.[8]

Instar — a stage in the life of an arthropod (such as an insect) between two successive moults.[43]

Integrated pest management — using a combination of management tactics to reduce pest numbers at tolerable levels in an economically and environmentally rational manner.[56]

Intraguild predation — predation of one natural enemy by another.

Laboratory immunoassays — methods of detection of plant pathogens using antibodies performed in a laboratory.[54]

Larva — the immature, wingless form that hatches from the egg of many insects, alters chiefly in size while passing through several moults and is finally transformed into a pupa or chrysalis from which the adult emerges.[43]

Latent period — the time during which a pathogen is present without producing symptoms.[54]

Light traps — a device for collecting or destroying insects that consists of a bright light in association with a trapping or killing medium.[43]

Mandibles — either member of the anterior pair of mouth appendages of an arthropod often forming strong biting jaws.[43]

Mass trapping — when traps are used to capture large quantities of arthropod pests in an effort to reduce pest pressure on the cultivated crop.

Maxilla (plural = maxillae) — one of the first or second pair of mouthparts posterior to the mandibles in many arthropods (such as insects or crustaceans).[43]

Maxillary palp — a small several-segmented process on the outer aspect of each maxilla of an insect that is believed to have a sensory function.[43]

Mechanical transmission — where the spread of a pest occurs through contaminated surfaces or materials. In greenhouses, this could occur through handling of plants, employees clothing, contaminated tools and equipment or even through insects.

Metamorphosis — a striking change of form or structure in an individual after hatching. Changes are regulated by moulting and juvenile hormones.[8]

Microbial — of, relating to, or caused by microbes[43]; **in pesticides** refers to containing living microorganism such as bacterial, fungi, viruses, protozoans, algae, mycoplasma, rickettsia and related organisms and associated metabolites (or by-products), that are used to control pests.[1]

Microbial vectors — a microorganism, such as fungi or bacteria, that transmits a pathogen from one organism or source to another.

Miticide (see acaricide)

Midgut — is the middle portion of the alimentary canal in insects that produces and secretes digestive enzymes and absorbs nutrients.[16]

Monocultures — the cultivation or growth of a single crop or organism especially on agricultural or forest land.[43]

Mode of action — an identified chemical pathway or interaction with a specific target site in insects or a specific cellular process in fungi, that determines how a pesticide works to inhibit growth or cause mortality of the target pest.[27],[34]

Moult — the biological process of shedding or casting off of an outer layer. Arthropods shed their exoskeletons for the purpose of growth or change in shape.[8]

Multiple resistance — resistance to two or more insecticides via multiple mechanisms of resistance in a single organisms.[34]

Mycelium (plural = mycelia) — a mass of branched, tubular filaments (hyphae) of fungi and is often submerged in the tissues of the plant host.[8]

Mycorrhiza (plural = mycorrhizae) — the symbiotic association of the mycelium of a fungus with the roots of a seed plant. The association is usually of mutual benefit (symbiotic).[8]

Native (also known as indigenous) pest — an organism that is natural to a region and causes damage to a cultivated host plant.

Necrosis — usually localized death of living tissue.[43]

Non-consumptive effects — impacts biological control agents have on pest populations that do not include killing and consuming their prey (including intimidation, harassing, reductions in feeding, egg laying, development, etc.).[36],[78]

Non-conventional pest control products — substances used by the general public for a variety of purposes, but which can be used as pest control products. For example, garlic powder or table salt, vinegar, plant extracts and oils.[1]

Non-native (also known as exotic or alien), invasive pest — an organism that has been introduced from other regions or countries and causes damage to a cultivated host plant or has negative impacts to ecosystem health and to people.[71]

Non-persistent virus — a plant virus that can be acquired within minutes and transmitted by an insect host over a short period of time (minutes).[31],[63]

Nymph — sexually immature form usually similar to the adult and found in certain insects and mites which have incomplete or hemimetabolic metamorphosis.[8]

Ocelli (also known as simple eyes) — a minute simple eye or eyespot of an invertebrate often used to detect light in arthropods.[43]

Oomycete — phylum of funguslike organisms in the kingdom Chromista. Oomycetes may occur as saprotrophs (living on decayed matter) or as parasites living on higher plants and can be aquatic, amphibious or terrestrial.[8]

Oospore — a sexual spore.[8]

Ovicidal — an insecticide effective against the egg stage.[43]

Ovi-larvicidal — an insecticide effective against the egg and larval stage.[43]

Palps (also known as pedipalps) — either of the second pair of appendages of various arthropods (such as an arachnid) that lie on each side of the mouth and often perform a specialized function (such as grasping or feeling).[43]

Parasitism — relationship between two organisms in which one benefits at the expense of the other, sometimes without killing the host organism.[8]

Parasitoid host-feeding — a parasitoid who feeds and develops within or on the bodies of other arthropods.[8]

Parthenogenesis — a reproductive strategy that involves development of a female (rarely a male) gamete (sex cell) without fertilization as seen in aphids.[8]

Pathogenic — causing or capable of causing disease.[43]

Pedipalps — see palps.

Persistent virus — a plant virus that can be acquired and transmitted by an insect host over long periods of time (hours to days or days to life) and sometimes pass on to their offspring.[31],[63]

Personal Protective Equipment (PPE) — protective devices, garments or coverings (such as respirators, helmets, face shields, boots or gloves) that are worn to minimize exposure to hazards that may cause injury or illness.[43]

Pesticide application technology — technology and equipment used to apply pesticides to their target.

Pesticide efficacy — is a measure of the level, duration and consistency of control provided by a pesticide.[59]

Pesticide resistance — their susceptible members are killed off and those resistant strains that survive multiply, eventually perhaps to form a majority of the population. Resistance denotes a formerly susceptible insect population that can no longer be controlled by a pesticide at normally recommended rates.[8]

Pheromone — any endogenous chemical secreted in minute amounts by an organism in order to elicit a particular reaction from another organism of the same species.[8]

Pheromone-baited trap — a trap using a lure infused with a pheromone intended to attract individuals of a certain pest species.

Phloem — a complex tissue in the vascular system of higher plants that consists mainly of sieve tubes and elongated parenchyma cells usually with fibers and that functions in translocation and in support and storage.[43]

Phylum — primary category in biological taxonomy especially of animals that ranks above the class and below the kingdom.[43]

Plant pathogens — a microorganism that causes disease in plants.[54]

Plasmodesmata — one of the cytoplasmic strands passing through openings in some plant cell walls and forming connections with adjacent cells.[43]

Proactive sampling — sampling for the purposes of diagnosing a pest before symptoms are present or obvious.

Proboscis — any of various elongated or extensible tubular processes (such as the sucking organ of a butterfly) of the oral region of an invertebrate.[43]

Prolegs — a fleshy leg that occurs on an abdominal segment of some insect larvae but not in the adult.[43]

Propagules (of pathogens) — a structure (such as a spore) that causes disease transmission.[54]

Pupa — the life stage in the development of insects exhibiting complete metamorphosis that occurs between the larval and adult stages. During pupation, larval structures break down, and adult structures such as wings appear for the first time. The adult emerges by either splitting the pupal skin, chewing its way out or secreting a fluid that softens the silk cocoon (if present). The process of pupation is controlled by hormones.[8]

Reactive sampling — sampling for the purpose of diagnosing a pest after symptoms are observed.

Residual activity — how long a pesticide is present to control the pest in relation to the length of time it takes to degrade.[54]

Resistance management — strategies used to prevent, reduce or slow down the development of pesticide resistance in pests.[27],[34]

Resistant host (or cultivar/variety) — refers to cultivated hosts that are free from pests or disease symptoms even with direct exposure (a plant is immune to a specific pathogen).[8]

Roguing — to free a crop from inferior, diseased or otherwise unwanted plants or seedlings.[54]

Safety Data Sheet (SDS) — is a summary document that provides information about the hazards of a product and advice about safety precautions.[11]

Sanitation — the promotion of hygiene and prevention of disease by maintenance of sanitary conditions (as by removal of trash).[43]

Saprophyte — organism that feeds on nonliving organic matter. [8]

Sclerotized shield — hardened especially by the formation of sclerotin, sclerotized insect cuticle.[43]

Semiochemicals — message-bearing chemicals produced by an organism that causes a behavioural response in another organism of the same or different species.[1]

Semi-persistent virus — a plant virus that can be acquired within minutes to hours and transmitted by an insect host over a moderate period of time (minutes to hours).[31],[63]

Sign — an objective evidence of plant disease.[43]

Site of action — within a mode of action, a specific target site within an insect (usually a receptor protein) or specific enzymes in a cellular process within fungi, which determines where the pesticide binds.[27],[34]

Soilborne fungi — fungi that is transmitted by or in soil.[43]

Solarization — the act or process of solarizing something such as through the use of solar energy to heat soil to a high temperature (as to control soilborne pests) in agriculture.[43]

Specialist predator — predator that feeds on few or one species of prey.[60]

Spiracles — a breathing orifice such as an external tracheal aperture of a terrestrial arthropod that in an insect is usually one of a series of small apertures located along each side of the thorax and abdomen.[43]

Sporangium (plural = sporangia) — a structure within which asexual spores are produced.[43]

Steam sterilization — A practice that uses a sheet of clear plastic film to concentrate the sun's heat or uses machines to generate heat to kill organisms in soil or soil-based growing media.[43]

Sterile insect technique (SIT) — temporary or permanent sterility of one or both of the sexes or preventing maturation of the young to a sexually functional adult stage.[4],[8]

Sticky cards — coloured cards (typically yellow or blue) that are covered in a sticky substance and used to capture flying insects to monitor or mass trap.

Stigmata - respiratory pores on the body.[8]

Stippling — small punctures in plant tissue where the cell contents have been removed, often by mites.

Stylet — a relatively rigid elongated organ or appendage such as a piercing mouthpart of an arthropod.[43]

Supplemental food — see food supplementation.

Supply chain — the chain of processes, businesses, etc. by which a commodity is produced and distributed.[43]

Susceptible host (or cultivar/variety) — refers to cultivated hosts that are subject to infestation/infection by specific plant pests and under optimal conditions may result in injury.[8]

Symptom — subjective evidence of disease or physical disturbance broadly; an evident reaction by a plant to a pathogen.[43]

Systemic pesticide — is a penetrant pesticide that is absorbed, water-soluble and taken up by and transported throughout the organism.[8]

Taxonomy — in a broad sense the science of classification, but more strictly the classification of living and extinct organisms.[8]

Temperature-dependant development — where the development rate (the inverse of development time) begins at a minimum temperature and increases slowly as temperature increases, often linearly, until it reaches an optimal level, after which it decreases rapidly to a maximum temperature where development ceases or death occurs.[61]

Thorax — the part of an animal's body between its head and its midsection as seen in insects.[8]

Tolerant host (or cultivar/variety) — refers to cultivated hosts that have reduced symptoms or pest development compared to susceptible hosts and suffer minimal injury.[8]

Translaminar pesticide — is a localized penetrant pesticide that is absorbed but remains in the area of initial plant contact with limited movement within the plant.[6]

Vaccine-like pesticides (also known as plant vaccines) — this is a proactive approach that offers cross-protection with an attenuated variant of a virus.[79]

Vasculature (also known as vascular system) — assemblage of conducting tissues and associated supportive fibres that transport nutrients and fluids throughout the plant body.[8]

Vector — an organism (such as an insect or fungi) that transmits a pathogen from one organism or source to another.[43]

Vent screening — exclusion screening covering vents in a greenhouse.

Vestigial — remaining or surviving in a degenerate, atrophied or imperfect condition or form.[54]

Viral protein — these include any proteins in the virion that may be products of the viral genome or incorporated from the host, including structural proteins, coat proteins or host cell-recognizing proteins.[32]

Virion — a complete virus particle that consists of an RNA or DNA core with a protein coat sometimes with external envelopes and that is the extracellular infectious form of a virus.[43]

Viroid — any of two families (Pospiviroidae and Avsunviroidae) of particles that consist of a small single-stranded RNA arranged in a closed loop without a protein shell and that replicate in their host plants where they may or may not be pathogenic.[43]

Virus — any of a large group of submicroscopic infectious agents that are extremely complex molecules, that typically contain a protein coat surrounding an RNA or DNA core of genetic material but no semipermeable membrane, that are capable of growth and multiplication only in living cells and that cause various important diseases in humans, animals and plants.[43]

Volatiles (also known as volatile organic compounds) — chemicals produced or released by organisms that may serve as communication and facilitate interactions related to growth, development, defence, propagation and life cycle.[7]

Window-paning — injury from chewing insects where they feel on plant tissue but leave a thin translucent layer of the epidermis.

Zoospore — a motile asexual spore.[8]

Zygospore — a thick-walled sexual spore that usually serves as a resting spore.[43]

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Appendix A. List of Arthropod Pests of Greenhouse Fruits and Vegetables in Ontario

LEGEND: H = Host – = Not Applicable

Pest			Host Crop					
Group	**Scientific Name**	**Common Name**	**Tomato**	**Pepper**	**Eggplant**	**Cucumber**	**Lettuce**	**Strawberry**
Aphids	*Aphis gossypii*	Melon aphid	H	H	H	H	H	H
Aphids	*Aulacorthum solani*	Foxglove aphid	H	H	H	H	H	H
Aphids	*Macrosiphum euphorbiae*	Potato aphid	H	H	H	H	H	H
Aphids	*Myzus persicae*	Green peach aphid	H	H	H	H	H	H
Aphids	*Chaetospihon fragaefolii*	Strawberry aphid	–	–	–	–	–	H
Beetles	*Anthonomus eugenii*	Pepper weevil	–	H	H	–	–	–
Beetles	*Acalymma vittatum*	Striped cucumber beetle	–	–	H	H	–	–
Beetles	*Diabrotica undecimpunctata*	Spotted cucumber beetle	H	H	H	H	H	H
Bore	*Ostrinia nubilalis*	European corn borer	H	H	H	H	–	–
Bugs	*Lygus lineolaris*	Tarnished plant bug	H	H	H	H	H	H
Flies	*Bradysia spp.*	Dark–winged fungus gnat	H	H	H	H	H	H
Flies	*Drosophila suzukii*	Spotted winged drosophila	–	–	–	–	–	H
Flies	*Scatella stagnalis*	Shoreflies	H	H	H	H	H	H
Flies	*Liriomyza sativae*	Vegetable leafminer	H	H	H	H	H	–
Flies	*Liriomyza trifolii*	Serpentine leafminer	H	H	H	H	H	H
Loopers	*Chrysodeixis chalcites*	Tomato looper	H	H	H	H	H	H
Loopers	*Chrysodeixis includens*	Soygean looper	H	H	H	H	H	H
Loopers	*Trichoplusia ni*	Cabbage looper	H	H	H	H	H	H
Mites	*Tetranychus urticae*[1]	Two–spotted spider mite	H	H	H	H	H	H
Mites	*Aculops lycopersici*	Tomato russet mite	H	H	H	–	–	–
Mites	*Polyphagotarsonemus latus*	Broad mite	H	H	H	H	H	H
Mites	*Phytonemus (=Tarsonemus) pallidus*	Cyclamen mite	H	H	–	–	–	H
Thrips	*Echinothrips americanus*	Poinsettia thrips/Japanese flower thrips/Impatiens thrips	–	H	H	H	–	H
Thrips	*Frankliniella tritici*	Eastern flower thrips	H	H	H	–	–	H
Thrips	*Frankliniella occidentalis*	Western flower thrips	H	H	H	H	H	H
Thrips	*Thrips parvispinus*	Pepper thrips	–	H	H	–	–	H
Thrips	*Thrips tabaci*	Onion thrips	H	H	H	H	H	H
Whiteflies	*Trialeurodes vaporariorum*	Greenhouse whitefly	H	H	H	H	H	H
Whiteflies	*Bemisia tabaci*	Silverleaf whitefly	H	H	H	H	H	H

[1] Includes *T. urticae* red form (often referred to as carmine mite).

Appendix B. List of Plant Pathogens of Greenhouse Fruits and Vegetables in Ontario

LEGEND: B = Bacteria F = Fungi O = Oomycete V = Virus H = Host – = Not Applicable

Plant Diseases			Host Crop					
Group	**Disease**	**Causal Organism**	**Tomato**	**Pepper**	**Eggplant**	**Cucumber**	**Lettuce**	**Strawberry**
Foliar and Fruit Diseases								
F	Alternaria leaf blight	*Alternaria spp. (including A. cucumerina)*	–	–	–	H	–	–
B	Angular leaf spot	*Xanthomonas fragariae*	–	–	–	–	–	H
F	Angular leaf spot	*Pseudomonas syringae pv. lachrymans*	–	–	–	H	–	–
F	Anthracnose	*Colletotrichum acutatum species complex (CASC)*	H	H	H	–	–	H
F	Anthracnose	*Colletotrichum coccodes*	H	H	H	–	–	–
F	Anthracnose	*Colletotrichum nymphaeae*	–	–	–	–	–	H
F	Anthracnose	*Colletotrichum dematium*	H	H	H	–	–	–
F	Anthracnose	*Colletotrichum gloeosporioides species complex (CGSC)*	H	H	H	–	–	H
F	Anthracnose	*Colletotrichum orbiculare*	–	–	–	H	–	–
B	Bacterial canker (bacterial stem canker)	*Clavibacter michiganensis subsp. michiganensis*	H	H	H	–	–	–
B	Bacterial speck (bacterial blight)	*Pseudomonas syringae pv. tomato*	H	H	H	–	–	–
B	Bacterial spot (bacterial blight, bacterial leaf spot)	*Xanthomonas spp. (including X. vesicatoria, X. auvesicatoria, X. gardneri, X. perfornas)*	H	H	H	–	–	–
B	Bacterial stem rot	*Pectobacterium carotovorum*	H	H	H	–	–	–
B	Bacterial wilt	*Erwinia tracheiphila*	–	–	–	H	–	–
B	Bacterial wilt	*Ralstonia solanacearum species complex (RSSC)*	H	H	H	H	H	H
F	Botrytis grey mould	*Botrytis cinerea*	H	H	H	H	H	H
F	Cercospora leaf spot	*Cercospora citrullina*	–	–	–	H	–	–
F	Cercospora leaf spot	*Peronospora effusa (syn. P. farinosa)*	–	–	–	–	H	–
F	Cercospora leaf spot	*Pseudoperonospora cubensis*	–	–	–	H	–	–
F	Cercospora leaf spot	*Bremia lactucae*	–	–	–	–	H	–
F	Early blight	*Alternaria solani*	H	H	H	–	–	–
F	Gummy stem blight	*Stagonosporopsis cucurbitacearum (syn. Didymella bryoniae), S. citrulli, S. caricae*	–	–	–	H	–	–
F	Internal fruit rot (inner rot)	*Fusarium fujikuroi species complex (FFSC) (including F. lactis, F. proliferatum)*	–	H	–	–	–	–
F	Internal fruit rot (inner rot)	*Fusarium oxysporum species complex (FOSC) (including F. oxysporum)*	–	H	–	–	–	–
O	Late blight	*Phytophthora infestans*	H	H	H	–	–	–
F	Leaf mould	*Passalora fulvum (syn. Fulvia fulva)*	H	–	–	–	–	–

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Appendix B. List of Plant Pathogens of Greenhouse Fruits and Vegetables in Ontario ***(continued)***

LEGEND: B = Bacteria F = Fungi O = Oomycete V = Virus H = Host – = Not Applicable

Plant Diseases			Host Crop					
Group	**Disease**	**Causal Organism**	**Tomato**	**Pepper**	**Eggplant**	**Cucumber**	**Lettuce**	**Strawberry**
Foliar and Fruit Diseases								
O	Leather rot	*Phytophthora cactorum*	–	–	–	–	–	H
F	Phomopsis leaf blight	*Phomopsis obscurans*	–	–	–	–	–	H
O	Phytophthora blight (Phytophthora foliar blight, Phytophthora fruit rot, buckeye rot)	*Phytophthora capsici (foliar phase)*	H	H	H	H	–	–
O	Phytophthora blight (Phytophthora foliar blight, Phytophthora fruit rot, buckeye rot)	*Phytophthora nicotianae*	H	H	H	–	–	H
F	Powdery mildew	*Leveillula taurica*	H	H	H	H	–	–
F	Powdery mildew	*Golovinomyces lycopersici (syn. Oidium lycopersici)*	H	H	H	H	–	–
F	Powdery mildew	*Pseudoidium neolycopersici (syn. Oidium neolycopersici)*	H	H	H	H	–	–
F	Powdery mildew	*Golovinomyces cichoracearum (syn. Erysiphe cichoracearum)*	H	H	H	H	H	–
F	Powdery mildew	*Sphaerotheca fuliginea (syn. Podosphaera xanthii, Podosphaera fusca)*	–	–	–	H	H	–
F	Powdery mildew	*Podosphaera aphanis (syn. Sphaerotheca macularis)*	–	–	–	–	–	H
F	Neopestalotiopsis leaf blight	*Neopestalotiopsis spp.*	–	–	–	–	–	H
F	Septoria leaf spot	*Septoria lycopersici*	H	H	H	–	–	–
F	Septoria leaf spot	*Septoria cucurbitacearum*	–	–	–	H	–	–
Root, Crown and Stem Rots and Wilts								
F	Black root rot, Bottom rot, Rhizoctonia root rot	*Rhizoctonia solani*	H	H	H	H	H	H
F	Black rot	*Diaporthe spp. (including D. sclerotioides (syn. Phomopsis sclerotioides), D. cucurbitae (syn. P. cucurbitae))*	–	–	–	H	–	–
F	Corky root rot	*Pyrenochaeta lycopersici*	H	H	H	H	H	H
F	Fusarium stem rot	*Fusarium solani species complex (FSSC) (including F. solani)*	H	H	H	H	H	H
F	Fusarium root rot	*Fusarium oxysporum species complex (FOSC) (including F. oxysporum)*	H	H	H	H	H	H
F	Penicillium stem rot	*Penicillium oxalicum*	–	–	–	H	–	–
O	Phytophthora root, Crown rot	*Phytophthora capsici (soil phase)*	H	H	H	H	–	–
O	Phytophthora root, Crown rot	*Phytophthora cactorum*	–	–	–	–	–	H
O	Pythium root rot, Damping off	*Pythium aphanidermatum*	H	H	H	H	H	H
O	Pythium root rot, Damping off	*Pythium dissotocum*	H	H	H	H	H	H

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Appendix B. List of Plant Pathogens of Greenhouse Fruits and Vegetables in Ontario ***(continued)***

LEGEND: B = Bacteria F = Fungi O = Oomycete V = Virus H = Host – = Not Applicable

Plant Diseases			Host Crop					
Group	**Disease**	**Causal Organism**	**Tomato**	**Pepper**	**Eggplant**	**Cucumber**	**Lettuce**	**Strawberry**
Root, Crown and Stem Rots and Wilts								
O	Pythium root rot, Damping off	*Pythium irregulare*	H	H	H	H	H	H
O	Pythium root rot, Damping off	*Pythium ultimum*	H	H	H	H	H	H
F	Neopestalotiopsis crown, Root rot	*Neopestalotiopsis spp. including Neopestalotiopsis rosae*	–	–	–	–	–	H
F	Sclerotinia rot (Sclerotinia drop, lettuce drop)	*Sclerotinia minor*	–	–	–	–	H	–
F	Sclerotinia rot (Sclerotinia drop, lettuce drop)	*Sclerotinia sclerotiorum*	H	H	H	H	H	H
Viruses								
V	Beet Pseudo-Yellows Virus (BPYV)	*Closterovirus*	–	–	–	H	H	H
V	Cucumber Green Mottle Mosaic Virus (CGMMV)	*Tobamovirus*	–	–	–	H	–	–
V	Cucumber Mosaic Virus (CMV)	*Cucumovirus*	H	H	H	H	H	H
V	Cucumber Necrosis Virus (CNV)	*Tombusvirus*	–	–	–	H	–	–
V	Impatiens Necrotic Spot (INSV)	*Tospovirus*	H	H	H	H	H	H
V	Pepino Mosaic Virus (PepMV)	*Potexvirus*	H	H	H	–	–	–
V	Pepper Mild Mottle Virus (PMMV)	*Tobamovirus*	–	H	–	–	–	–
V	Strawberry Crinkle Virus (SCV)	*Cytorhabdovirus*	–	–	–	–	–	H
V	Strawberry Mild Yellow Edge Virus (SMYEV)	*Potexvirus*	–	–	–	–	–	H
V	Strawberry Mottle Virus (SMoV)	*Sadwavirus*	–	–	–	–	–	H
V	Strawberry Vein Banding Virus (SVBV)	*Caulimovirus*	–	–	–	–	–	H
V	Tobacco Streak Virus (TSV)	*Ilarvirus*	H	H	H	H	H	H
V	Tobacco Mosaic Virus (TMV)	*Tobamovirus*	H	H	H	H	H	–
V	Tomato Brown Rugose Fruit Virus (ToBRFV)	*Tobamovirus*	H	H	–	–	–	–
V	Tomato Mosaic Virus (ToMV)	*Tobamovirus*	H	H	H	–	–	–
V	Tomato Spotted Wilt Virus (TWSV)	*Tospovirus*	H	H	H	H	H	H
V	Melon Necrotic Spot Virus (MNSV)	*Gammacarmovirus*	–	–	–	H	–	–

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Appendix C. Commercially Available Biological Control Agents for Major Greenhouse Pests in Canada

LEGEND: A = Primary prey/target B = Alternate prey/Contributes to reductin of pest population

Biological Control Agent	Arthropod Pest Attacked[1]									
	Common							Occasional		
Species	Aphids	Moths/ caterpillars	Fungus gnats	Mites	Shoreflies	Thrips	Whiteflies	Leafminers	Mealybugs	Weevils
Parasitoids (Parasitic wasps)										
Aphelinus abdominalis	A	–	–	–	–	–	–	–	–	–
Aphidius colemani	A	–	–	–	–	–	–	–	–	–
Aphidius ervi	A	–	–	–	–	–	–	–	–	–
Aphidius matricariae	A	–	–	–	–	–	–	–	–	–
Dacnusa sibirica	–	–	–	–	–	–	–	A	–	–
Diglyphus isaea	–	–	–	–	–	–	–	A	–	–
Encarsia formosa	–	–	–	–	–	–	A	–	–	–
Eretmocerus eremicus	–	–	–	–	–	–	A	–	–	–
Trichogramma brassicae	–	A	–	–	–	–	–	–	–	–
Trichogramma minutum	–	A	–	–	–	–	–	–	–	–
Trichogramma ostrinae	–	A	–	–	–	–	–	–	–	–
Trichogramma pretiosum	–	A	–	–	–	–	–	–	–	–
Predatory Insects (Beetles, midges, lacewings, bugs, flies)										
Adalia bipunctata	A	–	–	–	–	–	–	–	B	–
Aphidoletes aphidimyza	A	–	–	–	–	–	–	–	–	–
Cryptolaemus montrouzieri	–	–	–	–	–	–	–	–	A	–
Chrysoperla (=Chrysopa) carnea	A	B	–	B	–	B	B	–	B	–
Chrysoperla (=Chrysopa) rufilabris	A	B	–	B	–	B	B	–	–	–
Dalotia (=Atheta) coriaria	–	–	A	–	A	A	–	–	–	–
Delphastus catalinae	–	–	–	–	–	–	A	–	–	–
Dicyphus hesperus	B	–	–	B	–	B	A	–	B	–
Eupodes americanus	A	–	–	–	–	–	–	–	–	–
Feltiella acarisuga	–	–	–	A	–	–	–	–	–	–
Hippodamia convergens	A	–	–	–	–	B	–	–	B	–
Micromus variegatus	A	–	–	–	–	B	B	–	B	–
Orius insidiosus	B	B	–	B	–	A	B	–	B	–
Podisus maculiventris	–	A	–	–	–	–	–	–	–	–
Stethorus punctillum	–	–	–	A	–	–	–	–	–	–

[1] Biological control agents may have prefered species within these groups of pests.

[2] Microbial pathogens or their byproducts (excluding nematodes) used for pest management must be registered as a biopesticide through Health Canada under the *Pest Control Act*. Each product has specific uses on the label including approved applications by crop and pest. Each microbial species may have different strains that target different pest species. See labels for guidelines.

continued ››

Appendix C. Commercially Available Biological Control Agents for Major Greenhouse Pests in Canada ***(continued)***

LEGEND: A = Primary prey/target B = Alternate prey/Contributes to reductin of pest population

Biological Control Agent	Arthropod Pest Attacked[1]									
	Common							Occasional		
Species	Aphids	Moths/ caterpillars	Fungus gnats	Mites	Shoreflies	Thrips	Whiteflies	Leafminers	Mealybugs	Weevils
Predatory Mites										
Amblydromalus limonicus	–	–	–	B	–	A	A	–	–	–
Amblyseius andersoni	–	–	–	A	–	B	B	–	–	–
Amblyseius degenerans	–	–	–	B	–	A	B	–	–	–
Amblyseius swirskii	–	–	–	B	–	A	A	–	–	–
Anystis baccarum	A	–	–	A	–	A	B	–	–	–
Gaeolaelaps aculeifer (=Hypoaspis aculeifer)	–	–	–	–	–	A	–	–	–	–
Gaeolaelaps gillespiei	–	–	A	–	–	B	–	–	–	–
Neoseiulus (=Amblyseius) californicus	–	–	–	A	–	B	–	–	–	–
Neoseiulus (=Amblyseius) cucumeris	–	–	–	B	–	A	–	–	–	–
Neoseiulus (=Amblyseius) fallacis	–	–	–	A	–	B	B	–	–	–
Phytoseiulus persimilis	–	–	–	A	–	–	–	–	–	–
Stratiolaelaps scimitus (=Hypoaspis miles)	–	–	A	–	B	B	–	–	–	–
Entomopathogens[2] (Nematodes, fungi, bacteria, baculoviruses)										
Autographa californica Nucleopolyhedrovirus	–	A	–	–	–	–	–	–	–	–
Bacillus thuringiensis subsp. aizawai	–	A	–	–	–	–	–	A	–	–
Bacillus thuringiensis subsp. kurstaki	–	A	–	–	–	–	–	–	–	–
Bacillus thuringiensis subsp. israelensis	–	–	A	–	–	–	–	–	–	–
Beauveria bassiana	B	–	–	B	–	A	A	–	–	–
Lecanicillium muscarium	A	–	–	–	–	A	A	–	A	–
Metarhizium anisopliae	–	–	–	B	–	A	A	–	–	–
Steinernema carpocapsae	–	B	A	–	A	B	–	–	–	B
Steinernema feltiae	–	B	A	–	A	B	–	–	–	B
Steinernema kraussei	–	–	B	–	–	–	–	–	–	B

1 Biological control agents may have prefered species within these groups of pests.

2 Microbial pathogens or their byproducts (excluding nematodes) used for pest management must be registered as a biopesticide through Health Canada under the *Pest Control Act*. Each product has specific uses on the label including approved applications by crop and pest. Each microbial species may have different strains that target different pest species. See labels for guidelines.

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Appendix D. Ministry Resources

Agricultural Information Contact Centre
Provides province-wide, technical and business information to commercial farms and agri-businesses.
Tel: 1-877-424-1300
E-mail: ag.info.omafra@ontario.ca

ONGreenhouseVegetables

For the latest information on:

- Commercial controlled environment agriculture including greenhouse fruits, vegetables and vertical farming
- Timely updates and technical information on production and integrated pest management
- GrowON educational series workshops/webinars
- Greenhouse Vegetable Course

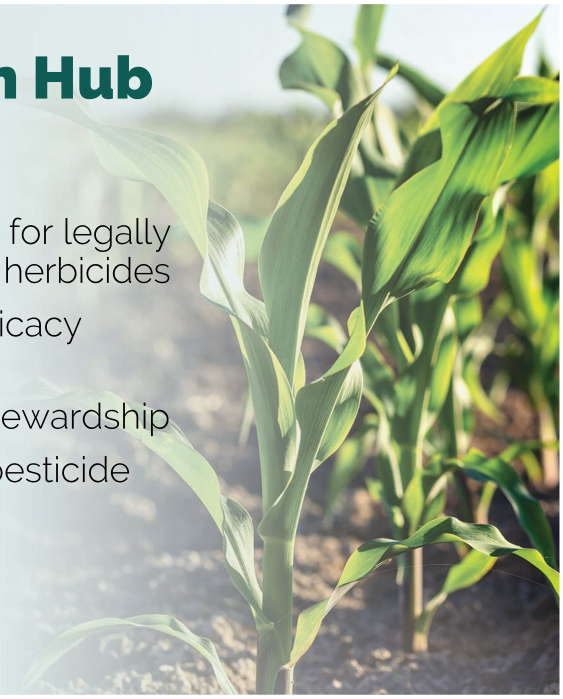
Visit the Blog at
ONGreenhouseVegetables.ca

Ontario Crop Protection Hub

Use this tool on any device to find:

- Proper rates and application protocols for legally registered insecticides, fungicides and herbicides
- Up-to-date information on product efficacy against pests
- Strategies to support environmental stewardship
- Information to help growers manage pesticide resistance

Visit the Ontario Crop Protection Hub at
Ontario.ca/cropprotection



CropIPM

IPM info at your fingertips. The new CropIPM tool includes:

- Up-to-date IPM information for key Ontario pests
- A new 'Identify' feature to help you identify pests and disorders
- An expanded offering of crop specific information
- Scouting calendars
- Comparisons of often-confused-with pests
- Details on soil diagnostics and herbicide injury

Visit the Crop IPM Tool at
Ontario.ca/cropIPM

Appendix E. Other Resources

Agriculture & Agri-Food Canada (AAFC)
Agriculture and Agri-Food Canada supports the Canadian agriculture and agri-food sector through initiatives that promote innovation and competitiveness.
https://agriculture.canada.ca/en
AAFC Research Centres
www.agriculture.canada.ca/en/agricultural-science-and-innovation/agriculture-and-agri-food-research-centres-and-collections

Canadian Food Inspection Agency — Plant Protection
Services and information on plant pests and invasive species, import, export, trade, fertilizers, soil and soil-related matter, grains and field crops, seeds, cannabis, forestry, horticulture. https://inspection.canada.ca/en/plant-health

Canadian Greenhouse Conference
The Canadian Greenhouse Conference is a not-for-profit corporation and Canada's foremost event and connection point for commercial growers of crops produced in a controlled environment.
https://www.canadiangreenhouseconference.com/

Greenhouse Canada
National business magazine published exclusively for commercial greenhouse growers in Canada.
https://www.greenhousecanada.com/

University of Guelph — Plant Agriculture
Canada's largest and most diverse applied plant biology department. A research intensive department within the Ontario Agricultural College dedicated to teaching, research and service related to horticultural crops, turfgrass, landscape species and field crops. www.plant.uoguelph.ca
Lab Services Division
www.uoguelph.ca/labserv/

Notes

ontario.ca/crops