STEWARDSHIP OF BIOLOGICAL CROP PROTECTION PRODUCTS AND THEIR ROLE IN IPM STRATEGIES

CropLife
INTERNATIONAL

1 INTRODUCTION

Aim of guideline - including what agents are covered

Biological control uses living organisms (substances derived from living organisms or naturally occurring compounds) to manage pest organisms, including insects, mites, diseases, nematodes, and weeds. Although they have been employed in niche markets and specialised situations for decades, in recent years their use has become more mainstream. In 2022, for example, the global market for biological crop protection products (biologicals) was estimated to be USD 6.6 billion. It is projected to reach USD 13.7 billion by 2027. Increasingly, they are an important tool within Integrated Pest Management (IPM) strategies, particularly for insect control, where most commercially available biological options exist. As they have very different modes of action from one another and from synthetic chemical pesticides, they (particularly microbial pesticides) are effective tools within a resistance management programme. Due to their nature, they need to be stored, handled, and used appropriately in order to work effectively and safely. These guidelines outline the recommended stewardship practices that should be employed to achieve this with commercially available biological products, including safety guidelines and how they can be usefully included in IPM strategies. As more biological solutions have been developed for arthropod pests, this forms the main focus of these guidelines. However, with regards to stewardship recommendations, these are normally the same for all pest types. For example, the storage, handling, and use of fungi are the same whether they are used to control insects or diseases.

Target audience

The main target audience for these guidelines is crop protection industry staff, pest management advisors, growers and applicators who will use biologicals, as well as those in the supply chain that would be handling and supplying them. They also provide useful information for regulators and other government officials on the role of biologicals in crop protection and how they should be used.

Types of biologicals covered in these guidelines

Biologicals can be classified into four main groups:

- **Macrobial agents** – arthropod natural enemies of pests that control through parasitism or predation; commonly these are insect or mite species.
- **Microbial agents** – these include viruses, fungi, bacteria, entomopathogenic nematodes and microsporidia. These may be living and dead cells or associated materials, as well as entire microorganisms.
- **Semiochemicals** – substances emitted by animals, plants and other organisms for communication and that impact either the same species or a different species.
- **Natural substances** – natural substances originating from plants, animals, and microorganisms (e.g. botanicals, fermentation products).

Biologicals can include some new, upcoming technologies, such as RNA interference (RNAi). These guidelines focus on those agents that are commercially available and therefore can be used. Guideline updates will broaden coverage as more products become commercially available. A more detailed description of agents covered is provided in section two.

DESCRIPTION OF BIOLOGICALS

Macrobial agents

Macrobial agents are arthropod parasitoids and predators. Irradiated insects for use in Sterile Insect Technique (SIT) can also be included here.

Types of biological control with macrobial agents

There are various forms of biocontrol: classical, new association, conservation, and augmentation (inoculative and inundative).

Classical biological control

Classical biocontrol is the intentional introduction of an exotic, usually co-evolved, biological control agent for permanent establishment and long-term pest control. This happens when an exotic pest is introduced into a new region, usually accidentally with an introduced plant type, and the natural enemies of the new pest are absent from the new region. Classical biocontrol has a history of safety. Despite the over 5000 introductions of more than 2000 species of arthropod biocontrol agents globally in the last 100 years or more, there have been very few reports of negative non-target effects.

New association biological control

New association biological control is the intentional introduction of an exotic, non-co-evolved (i.e. new association) biocontrol agent for permanent establishment and long-term pest control. This approach is far less common than classical biocontrol.

Conservation biological control

Conservation biocontrol is the modification of the environment or existing practices to protect and enhance specific natural enemies or other organisms, already resident in the environment, to reduce the effect of pests.

Augmentation biological control

The term, augmentation, implies that the biocontrol agent being released, already occurs in the agricultural setting in which it will be released. By augmenting it, one is simply attempting to improve upon the efficacy of the biocontrol that is already in existence in the agricultural ecosystem. Augmentation is not a panacea for managing a pest outbreak. If a pest outbreak occurs, it is often an indication that the natural enemy complex of the pest has been disrupted and the environment is thus not conducive to proliferation of these natural enemies. Releasing further natural enemies into such an environment will not solve the problem that exists with the environment. Consequently, for augmentation biocontrol to be effective, the crop in question must already be under good IPM, with a good level of natural biocontrol occurring. There are two general types of augmentation.

Inoculative augmentation

Inoculation biocontrol is the intentional release of a living organism as a biocontrol agent, with the expectation that it will multiply and control the pest for an extended period, but not permanently. Very often, the initial numbers of biocontrol agents released are not sufficient to have an immediate noticeable impact on the target pest. This will only be seen with subsequent generations, once the biocontrol agent numbers have built up to an influential level. Consequently, in order for this approach to work, augmentation must be initiated early in the season, so there is sufficient time for the released biocontrol agents to build up their numbers and bring the pest under control.

Inundative augmentation

Inundation biocontrol is the use of living organisms to control pests when control is achieved exclusively by the released organisms themselves. Consequently, unlike inoculative augmentation, initial numbers of biocontrol agents released are sufficiently high to have an immediate impact on the target pest. Early release of biocontrol agents, while the pest population is still low, is therefore not a prerequisite for efficacy with this form of augmentation

Parasitoids

Parasitic wasps

These are a large group of hymenopteran insects that are usually very small and lay their eggs in or on host insects, such as caterpillars and aphids. Larvae that hatch from the host feed on and kill the host. Some species lay their eggs and complete development in the eggs of the host. A commonly used example is *Trichogramma* wasps.

Parasitic Flies

These are dipteran insects that look like houseflies. The most common group is tachinids. In some species the adult deposits eggs in or on the host, whereas other species' eggs are laid on foliage eaten by the host. Hatched larvae feed internally on the host and kill it. The most common hosts are caterpillars.

Strengths and weaknesses of parasitoids

Strengths	Weaknesses
Searches for pest	Slow to work
Can control over large areas	Sensitive to environmental conditions
Can suppress population over long periods	Living organisms, so very short shelf life
No residue issues	Potentially sensitive to chemical sprays
No secondary pest repercussions	Generally, species-specific
No development of resistance	

How to use parasitoids

As well as providing natural control through conservation, parasitoids can be utilised by releasing large numbers in the field when the pest insect is at the appropriate stage in its life cycle to be parasitized. It is important to follow supplier instructions on release container positioning, density, and timing.

Predators

These are predatory arthropods, where the adult and/or juvenile stages eat the pest arthropod.

Beetles

The main groups of beetles that predate pests are ground beetles (Carabidae), rove beetles (Staphylinidae), both of which are generalist predators of mainly soil-dwelling life stages of insect pests, and ladybugs (Coccinellidae), which prey on scale insects, mealybugs, aphids, and mites. Some of the larger ground beetles also feed on slugs and worms. Rove beetles are generalist predators and ladybugs most often feed on scale insects, mealybugs, and aphids.

Mites

These are arachnids (spider class). They can predate the eggs and juvenile stages of small insects such as thrips, whitefly, and scale insects. They are mainly used to control spider mites and other pest mites, feeding on all life stages (eggs, nymphs, and adults).

Bugs

These are hemipteran insects that kill the prey by piercing the host with their mouthparts and sucking out the body fluids. A common example is the minute pirate bug (Orius spp.), which predates several pest species, including aphids, thrips, small caterpillars, and mites.

Lacewings

These winged insects are in the order Neuroptera. The larvae eat several pest species, including aphids, mealybugs, thrips, and mites, using pincer-like jaws to hold the pest and inject it with a toxin. They then suck out the body fluids. Adults also predate the same pests, but feed at a lower rate.

Strengths and weaknesses of predators

Strengths	Weaknesses
Searches for pest	Slow to work
Can suppress population over long periods	Sensitive to environmental conditions
Leave no residues	Living organisms, so very short shelf life
Often less species-specific than parasitoids	Potentially sensitive to chemical sprays
No secondary pest repercussions	Sometimes only high-density feeders
No development of resistance	

How to use predators

Like parasitoids, predators are important in natural control, and measures such as habitat maintenance and areas that are not sprayed with chemical pesticides are employed. As with parasitoids, predators can also be released argumentatively. Again, it is important that supplier instructions for release are followed.

Sterile Insect Technique

The Sterile Insect Technique (SIT) consists of the mass release of sterile males (and sometimes also females) of the same species as the pest into the environment to provide area-wide control. The released insect vastly outnumbers the naturally occurring pest, meaning that the wild, fertile females are more likely to pair with the sterile males rather than a wild, fertile male, leading to population suppression. The sterile males are mass-reared in a specialised facility and sterilised by irradiation with, for example, gamma rays or X-rays. First used in the 1950s to control the screwworm that attacks cattle, it has now been used to control crop pests such as fruit flies, codling moth, false codling moth and pink bollworm. SIT is the ultimate area-wide pest control technology, as no other technology, even those that are semiochemical based, can so effectively be applied over an entire area, including areas of natural vegetation and urban areas. By so doing, the target pest population is suppressed, rather than just managing the pest in a specific cropping area e.g. farm or plot.

Strengths and weaknesses of SIT

Strengths	Weaknesses
Searches for pest	Control occurs over time – seasons or years
Can suppress population over large areas, even beyond the crop	Migration of non-sterile insects into the treated area needs to be prevented
Leave no residues	Living organisms, so very short shelf life
No development of resistance	Laboratory rearing may reduce performance at cold temperatures relative to wild counterparts
Highly species-specific	Irradiation may reduce fitness relative to wild counterparts
No non-target effects	Releases need to be conducted at very frequent intervals
No more sensitive to chemical sprays than the wild pest	

How to use SIT

Large numbers of sterile insects are released into the (often very large) treatment area on a regular basis.

Microbial agents

Microbial agents are microorganisms that infect and normally kill a pest or in some cases, compete with the pest. The most common are entomopathogens used for insect control are viruses, fungi, entomopathogenic nematodes, bacteria, and microsporidia. Bacteria or fungi are also used for disease control and have been evaluated for weed and plant parasitic nematode control.

Viruses

Entomopathogenic viruses used for pest control are members of the Baculoviridae family (baculoviruses). They are generally restricted to insect (mainly lepidopteran) hosts and are incapable of replicating in mammal or plant cells and are thus considered very safe. These viruses have one or more virus particles embedded in a protein occlusion body. Although the occlusion body gives some protection to the virus from environmental conditions, baculoviruses can be rapidly inactivated by ultraviolet radiation from the sun, as well as high temperatures. The host insect ingests the virus, which then infects it via the midgut. Once in the haemolymph ("blood"), the virus infects and replicates in the insect cells, liquifying organs. Eventually, the insect itself ruptures releasing the liquified body contents, containing large amounts of occluded virus, which can then infect further hosts. There are two types of baculoviruses – the nucleopolyhedroviruses (NPVs) and the granuloviruses (GVs), both have been used as microbial pesticides, providing direct control of insect pests, as well as, initiating disease in the pest population (epizootic).

NPVs

The NPVs have several virus particles embedded in the occlusion body. They mainly infect the larvae of lepidopteran species (caterpillars), but some also infect some hymenopteran (wasps, bees, and ants) and dipteran (fly) hosts. A number of NPVs have been commercialised to control some major pests, such as cotton bollworm (Helicoverpa spp.), cotton leafworm and armyworms (Spodoptera spp.), Gypsy Moth (Lymantria dispar) and some sawfly species (Neodiprion spp.).

GVs

GVs normally have a single virus particle within the occlusion body. They are specific to the larvae of lepidopteran species and have been commercialised as microbial insecticides to control some major pests, such as the codling moth (Cydia pomonella), false codling moth (Thaumatotibia leucotreta) and the diamondback moth (Plutella xylostella).

Strengths and weaknesses of baculoviruses

Strengths	Weaknesses
Highly specific and suitable for use in ecologically sensitive areas	Slow acting
Can spread horizontally within a population	Migration of non-sterile insects into the treated area needs to be prevented
Environmentally safe and has no significant non-target effects	Have to be ingested
No harmful residues on the crop	Usually only infect larval stages and less virulent against larger larvae
Resistance is very rare	Generally, species-specific (although also a strength)
Extremely persistent in the environment, where protected	Sensitive to sunlight and high temperature, which can negatively affect persistence
Generally compatible with chemical pesticides	Need to be stored refrigerated
Excellent shelf-life when refrigerated	

How to use baculoviruses

Mainly used as a microbial insecticide, being applied in the same manner as a chemical pesticide.

Fungi

Although there are entomopathogenic fungi (EPF) from several fungal groups, the most important for pest control are Ascomycota, in particular Beauveria spp. that target a wide range of insects, including cotton bollworm and coffee berry borer, Hirsutella spp. that infect spider mites; Isaria spp. against whitefly and psyllids, Metarhizium spp. that are used to control various beetles, caterpillars, locusts and grasshoppers and termites, and Lecanicillium spp. against mealybugs and sucking insects. One species, Paecilomyces lilanicus, is used to control plant parasitic nematodes. Normally these fungi infect the host when it comes in contact with the fungal spores, which germinate and penetrate the host cuticle (outer layer) into the body cavity where the fungal cells grow. The fungus normally kills the insects and sporulates from the disintegrating body, releasing spores that can infect further hosts. Although they can cause epizootics (outbreaks), they are most commonly used as microbial pesticides. Generally, entomopathogenic fungi are specific to insects. Those developed as microbial insecticides are strains that do not produce toxins and cannot grow at human body temperatures.

Strengths and weaknesses of fungi

Strengths	Weaknesses
Specific to insect groups and some nematodes	Sensitive to high temperatures and UV radiation, which can negatively affect persistence of the plant
Attack both juveniles and adults	Require high humidity (>98% for germination – can be overcome by oil-based formulation)
Contact action (do not need to be ingested)	Slow acting
Can trigger epizootics	May be pest-density dependent to achieve good efficacy
No residue problems	
Resistance is rare	
Extremely persistent in the soil environment	
Generally good shelf-life	

How to use fungi

Mainly used as a microbial insecticide, ideally timing application for when host insect eggs are hatching, or when young juvenile are present.

Nematodes

Entomopathogenic nematodes (EPN) are soil-dwelling small soft-bodied, non-segmented roundworms that parasitise (normally) ground-dwelling insects. The free-living juvenile stage searches for its host and enters into the haemocoel (body cavity), via the spiracles (respiratory openings), anus and mouth or through intersegmental membranes in the cuticle. Once in the haemocoel, they release symbiotic bacteria from their intestines. The bacteria multiply in the haemocoel and kill the host, after which the nematodes feed on the host tissue and continue to develop and reproduce. Eventually, large numbers of juveniles are released from the host cadaver to infect more hosts. Although not a microorganism, they are classed as microbial insecticides, as they can be applied in a similar way as other microbial insecticides and it is their symbiotic bacteria that kills the host. There are two families and genera of entomopathogenic nematodes used in pest control – Heterorhabditis (symbiotic bacteria Photorhabdus) and Steinernema (associated bacteria Xenorhabdus). Targets include white grubs e.g. Japanese beetle, black vine weevil, cutworms, rootworms, and any arboreal pests that have a soil-dwelling life stage.

Strengths and weaknesses of nematodes

Strengths	Weaknesses
Able to search for host (over short distances)	Broad host range
Broad host range	Generally limited to the soil environment
No residue problems	Require moisture in soil
Limited dispersal ability, reducing non-target effects	Sensitive to freezing, high temperatures, desiccation, UV-light
Good persistence where soil remains moist and hosts are available	Limited storage time 2-5 months (no dormant stage)

How to use nematodes

Can be sprayed or applied through irrigation, generally to the soil or sometimes to the tree trunk. Timing should be when pupal and larval stages are present.

Bacteria

Bacteria are single-celled prokaryotic organisms. Those used for pest control generally are spore-forming bacteria (they form a protective spore around the vegetative bacteria). One species, *Bacillus thuringiensis* (Bt) is the most widely used microbial pesticide, globally. In this species, when the bacteria sporulates, it produces a protein crystal in a parasporal body that is toxic to some insect species. When the spore is ingested by the host insect, the toxin is released and breaks down the gut wall of the host. This allows bacteria to enter the haemocoel and multiply, causing septicaemia and death. Any bacteria in the gut can cause the septicaemia, thus Bt can be used even when the vegetative bacteria have been killed. This also has meant that the genetic code for production of the toxic protein can be inserted into crop plants to produce varieties that are resistant to some pests (e.g. Bt corn resistant to European corn borer). Bt is mainly used to control caterpillars (Lepidoptera), but varieties have also been commercialised to control beetles (notably the Colorado potato beetle), as well as public health pests, such as mosquitoes and black fly.

Other *Bacillus* species that have been commercialised include *Bacillus popilliae* for use against Japanese beetle. This is also a spore-forming bacteria but does not produce a toxin; rather the bacteria multiply in the beetle larvae, preventing larval maturation. *Bacillus lentimorbus*, used against some scarab beetles (white grubs) acts in a similar way. In both cases, the disease caused is referred to as a milky disease, as infected larvae take on a whitish hue.

Finally, some bacteria species e.g., *Streptomyces* spp. and *Saccharapolysopa* spp. produce metabolites that have insecticidal properties and once extracted in fermentation vessels are used as insecticides.

Strengths and weaknesses of bacteria

Strengths	Weaknesses
Spore provides some environmental protection	Sensitive to high temperature and UV radiation, which can negatively affect persistence
Normally reduce feeding; faster acting than most microbials	Must be ingested
No residue problems	Only effective against young larvae
Minimal non-target effects	Resistance more likely than with other entomopathogens

How to use bacteria

Generally applied as a spray to areas where the pest feeds and aimed at small larval stages.

Microsporidia

Microsporidia are spore-forming, one-celled parasites. Originally regarded as protozoa, they are now classified as a class within the Fungi Kingdom. When the spore is ingested by the host, it germinates, forming a tube that penetrates the gut epithelium (outer layer), infecting the cell and cytoplasm (cell liquid). With regard to crop pest control, *Paranosema locustae* (previously known as *Nosema locustae*) has been commercialised for the control of rangeland grasshoppers. Infection results in reduced feeding, development, and fecundity, as well as increased mortality, resulting in population suppression.

Strengths and weaknesses of microsporidia

Strengths	Weaknesses
Long-term population suppression	Slow acting
No residue problems	Suitable for area-wide management rather than small cropping areas
Generally, species-specific, so no non-target effects	Must be ingested
	Sensitive to UV radiation
	Very few examples of good efficacy in the field

How to use bacteria

Spray, targeted at third instar (life stage) nymphs

Microbials for disease and weed control

Microorganisms have also been used for disease control. Most notably, the fungi Trichoderma spp. have been widely used for control of a range of (mainly soil-borne) diseases. This microorganism antagonises fungal diseases through competing for nutrients and space, secretion of secondary metabolites and mycoparasitism, as well as inducing host plant resistance. The bacterium, Bacillus subtilis, has been marketed for fungal and bacterial disease control. In both cases, the beneficial microorganism is applied as a spray, but application as dust or granules and as a seed treatment have also been used. Trichoderma spp. and mycorrhizal fungi have also been used as resistance inducers against plant-parasitic nematodes, whereas Bacillus spp. and the fungus Paecilomyces lilacinus have been registered as control treatments against nematodes.

Bioherbicides have also been registered to control some weeds, mainly in North America. These include the fungus, Colletotrichum gloeospriodes, targeted at Northern jointvetch and round leaf marrow and the bacterium, Pseudomonas fluorescens, targeted at Downy brome and Green foxtail. These can be applied as a spray or granules. Generally, these microorganisms are no longer commercially available. Like microorganisms for insect control, those used for disease and weed control are sensitive to heat, humidity and UV light.

Botanicals

Botanicals are extracts/derivatives of plants that either kill a pest, or function as repellants, attractants, antifeedants or growth inhibitors. The majority of botanicals are used to control insect pests, with a number being commercialised, including extracts from pyrethrum (Tanacetum cinerariifolium) and Neem (Azadirachta indica), being the most widely commercially available and used. However, botanicals from numerous different plant species have been used for disease control, including garlic and chilli. Their impact has been questioned.

Strengths and weaknesses of botanicals

Strengths	Weaknesses
Often those used commercially have low toxicity to humans and livestock	Short persistence in the field (degraded rapidly by UV)
Generally, no residue issues in contrast with other chemicals, due to the more rapid breakdown of residues, but some do have set maximum residue levels;	Generally slow acting (often functions as deterrent rather than kill)

How to use botanicals

Normally applied like synthetic pesticides (spray application).

Semiochemicals

Insect behaviour-modifying semiochemicals, most notably insect sex pheromones, have been extensively used in pest management, both for controlling the pest insect, but also for population monitoring. Semiochemical-based technologies include mating disruption, attract, and kill and mass trapping.

Mating disruption (MD)

This is where a (synthetic) version of the female sex pheromone that attracts the male to the female for mating is distributed in a crop, resulting in interference of mate finding and suppressing pest reproduction.

Competitive MD

Males are diverted from orienting to females due to competing attraction of nearby false trails emanating from pheromone Dispensers.

Non-competitive MD

Where exposure to synthetic pheromone subsequently reduces or blocks the male's ability to sense pheromone normally. This could be achieved by negating the male's ability to respond to pheromone or by camouflaging the location of a pheromone-emitting female.

Attract and Kill

This is where a pheromone or other attractant is used to attract the pest insect to a trap or target, which is treated with (normally) a synthetic insecticide that will kill the adult insect.

Mass trapping

The female insect sex pheromone is placed in a trap, a sticky trap for example, which attracts and then traps the male. This is often used for pest monitoring, but also for control. The advantage of this method over Attract and Kill, is that one can determine the pest levels present and thus also when they decline, presumably due to the efficacy of the Mass trapping technology.

Strengths and weaknesses of semiochemical technologies

Strengths	Weaknesses
Effective over an extended period and area	Point sources need to be optimised i.e. placed at the ideal density and height for maximum efficacy
	Require high humidity (>98% for germination – can be overcome by oil-based formulation)
Can be used area-wide in different crops	Application specifications will differ for each pest and crop
No residue on crop	Species-specific
Safe to beneficials	If unprotected against direct sunlight, can rapidly break down due to UV radiation
Can be applied area-wide or in spot treatments	Temperature affects pheromone release rate/volatility
Does not need to be targeted to insects' exact location	Attract and kill normally has a high concentration of synthetic insecticide at the point source.
Attract and kill restricts the synthetic insecticide to a limited (controlled) area	

How to use semiochemical technologies

Applied early in the season when the pest first appears. Applied as a microencapsulated spray or as point source – trap, twist tie, etc.

Insecticidal soaps and oils

Oils, such as citrus oil, neem oil, essential oils (plant extracts), mineral and petroleum oils and specialised soaps are normally used to control soft-bodied, slow-moving insects, including those with a wax covering. These oils may be minimally toxic to the target insect and kill it through physical smothering.

Strengths and weaknesses of insecticidal soaps and oils

Strengths	Weaknesses
	High-volume sprays usually required
Few residue problems compared with other chemicals	Phytotoxicity may be an issue
Can control several species	Can impact non-pest species
Minimal non-target effects	High temperature and low humidity can increase phytotoxicity risk
Kills rapidly	No or little residual efficacy (purely contact action)

How to use insecticidal soaps and oils

Spray application directly on the pest insect and apply as a high-volume full-cover spray, as killing is often purely through physical smothering. Spray at a time in the crop phenology when phytotoxicity risk is at its lowest.

Fermentation products

Solid-state fermentation is a biotechnological process in which microorganisms grow on the solid substrate in the absence, or near-absence of water but with enough moisture to support their growth. Submerged (or liquid) fermentation is usually conducted with either dissolved or suspended substrates, in an aqueous medium. Avermectin and spinosad, which are produced by Streptomyces avermitilis, and Saccharopolyspora spinosa, respectively, are the most successful insecticide products produced through solid fermentation. Bacterial, fungal, and nematode-based biopesticides are also often produced through a fermentation process.

Strengths and weaknesses of fermentation products

Strengths	Weaknesses
May work as well as conventional chemical pesticides	May have some non-target effects
	May leave detectable residues
	Prone to the development of resistance

How to use fermentation products

Applied in the same manner as conventional pesticides.

2 STEWARDSHIP OF BIOLOGICALS

In this section, we provide general and specific guidelines for transportation, storage, application, safe usage, and waste management for all of the groups of biologicals. However, it is important to bear in mind that there may well be country-specific regulations, particularly pertaining to safety and waste disposal, which must be followed e.g. use of some PPE may be mandatory. In all cases, the starting point of stewardship is the following of all instructions and advice on the product label, which normally include use instructions, safety instructions, storage requirements and expiry date. Additional information will be included in the Safety Data Sheet, if available (this is produced for the registration process, if relevant, and should be available online).

These current guidelines provide advice on minimum or additional practices that may be beneficial or desirable. Regarding safety, each group of biologicals differs, as explained below. However, it is good practice, as a default to use basic PPE for the preparation (mixing, etc) and application of biologicals, even if considered safe. The relevant CropLife International guidelines should be consulted. Basic PPE consists of long-sleeved shirt and long trousers (or a coverall), boots or sturdy shoes and gloves, additionally for mixing eye protection and a mouth covering is recommended. Exposed areas should always be washed with soap after mixing or application.

For all biological products, weather conditions at the time of application must be suitable. These should be specified for all products or types of biologicals. Factors to consider are precipitation, windspeed, temperature, relative humidity, and UV radiation.

As with all pesticide use, detailed records of product application must be kept, including production name, rate used, date and time of application.

Macrobial agents

Challenges/unique properties

Macrobial agents are arthropod parasitoids and predators. Irradiated insects for use in SIT can also be included here. The main challenge of macrobial agents would be that they are living organisms with an extremely limited shelf-life and period of efficacy in the field. This creates challenges for the producer, the supply chain, and the end-user. For the producer, any interruption or decline in production would have an immediate impact on their business and on the client, for which there would be no quick fix.

Transport

The supply chain must ensure rapid delivery to the end-user (usually the grower) while maintaining the product under optimal conditions, which is usually either in a non-active life-stage (e.g. parasitized egg or pupa) or cooled to a temperature that prevents activity, while maintaining product quality. Sterile insects for SIT are always transported for release as adults and must therefore be kept at a cold temperature that prevents activity. This is especially important, if both the females and males of the species are used, as mating, which is the sole purpose of these irradiated insects, must not be allowed to occur prior to release.

Storage

Due to the limited shelf-life of almost all macrobial biocontrol agent products, storage for any length of time is usually not recommended. However, if immediate release is not possible, the supplier may recommend that the product be stored at a cool temperature, probably not refrigerated, for a short period of time before release. If the product is supplied in a non-active life stage, storage for a few days may even be possible. Irradiated insects for SIT must be stored at the same temperature used during transportation. Macrobials should always be stored in a dedicated space, separately from conventional crop protection products.

Application

On receipt of the product, the end-user must usually release the organism immediately, in the manner recommended by the supplier. Macrobial agents should be supplied in containers that make their release within a cropping system easy to conduct. The distribution of release points would depend on the dispersal ability of the biocontrol agent. Flighted insects can be released at greater distances apart throughout the crop, whereas non-flighted arthropods may need to be released onto every plant in the cropping area. The mode of release will depend on the specific natural enemy and the innovativeness of the product supplier. However, most macrobial agents will be supplied in a form where they can voluntarily exit the release container and begin dispersing and searching for the host.

Parasitoids are usually distributed as eggs or pupae. If the macrobial agent is an inoculative release candidate, as is usually the case with parasitoids, as previously explained, releases must be initiated early in the season. This will provide sufficient time for the parasitoid to build up to an effective level so that the target pest is under good control before harvest. If the natural enemy species being released is a species that is already present in the cropping environment, i.e. genuine augmentation, only initiating releases at a time that the natural population has already built up its numbers will often be superfluous.

Predators are typically released in their adult stage. When releasing predators, it's important to think about how far they can spread out, which depends on whether they can fly (like beetles and lacewings) or not (like mites). Predators are often inundative in their effect and often also high-density feeders, such as lady beetles, thus appropriate for release only once pest levels have built up. The impact of an inundative augmentation candidate will be almost immediate after release, similar to an insecticide.

Sterile insects are usually released on an area-wide basis (often very large areas) by the supplier. This is either done aerially or from the ground and must be repeated at frequent intervals, depending on the reproductive period of the released individuals. In order for SIT to be effective, the ratio of sterile to wild insects must be as high as possible. In order to achieve this, releases must be initiated early in the season, before the pest population has time to build up its numbers. Ratios of sterile to wild insects can be determined through trapping, as long as there is a reliable means to differentiate between the two. If ratios of sterile to wild are not high enough, release numbers of sterile individuals can be increased. Migration of fertile insects into the treated area is often prevented by trapping and/or chemical sprays outside the treated area.

It's important to also think about whether the released agent, especially parasitoids and predators, can be harmed by pesticide sprays and any leftover chemicals. The product supplier ought to be able to provide such information. Otherwise, there are other sources of such data, such as the IOBC (International Organisation for Biological Control) non-target effect database. This information will guide how long before or after the use of insecticides, parasitoids and predators should be released to ensure their efficacy. Optimum timing of release is often on the product label and should be followed, but generally, releases should be avoided during adverse weather conditions e.g. heavy rain or high winds, particularly if the flying adult stage is released.

Safety

Humans

The probability of risks to humans is considered remote and limited to allergic reactions and bites and stings. Personnel involved in the production of macrobial agents are most likely to be exposed and protection measures should be introduced to minimise such risks. However, even here, there have apparently been very few reports of allergies amongst such personnel, and any species that causes problems would be rapidly withdrawn. Thus, the sort of contact that the end-user has with these macrobial agents ought not to be problematic. Consequently, use of PPE when releasing these biocontrol agents is not necessary.

Environment

Macrobial agents are also completely non-toxic to the environment. In most cases, augmentation is conducted with species that are established in the environment into which they are being released. However, even introduction of exotic biocontrol agents has a rich history of safety, with very few cases of detrimental effects on the environment, including non-target effects on beneficial insects.

Waste management

Waste management would entail responsible disposal of the dispensing containers, which may need to be retrieved from the field post-release. Some suppliers do use biodegradable packaging.

Microbial agents

Challenges/unique properties

The majority of microbial agents are applied in a resting stage, the exception being some bacteria and nematodes. In all cases, however, they are sensitive to high temperature and ultraviolet radiation.

Transport

Like all pesticides, microbial agents should be transported separately from food and other household items. Due to their sensitivity to high temperatures and ultraviolet radiation, they preferably should be placed in a refrigerated container and away from direct sunlight.

Storage

Storage conditions and shelf-life should be on the product label. Generally, storage should be under refrigerated conditions, away from direct sunlight and in a dedicated storage space away from chemical pesticides. Once a container is opened the shelf-life could be drastically shortened. For example, dry formulations can deteriorate rapidly if the moisture content rises beyond 5%. This means that only enough product that is needed should be purchased. With nematode products, the infective juveniles are not in a resting stage but are immobilised to preserve their energy (for example, in polyurethane sponge).

Application

Most microbials are applied using pesticide spray application equipment, although (particularly) for fungi, baits and traps are also employed. In the former case, application should be targeted to where the pest is located (even for entomopathogenic nematodes as they do not move far). In all cases, timing of application/distribution should be for the most susceptible stage of the pest and, particularly for products that require digestion and for control of diseases, where the pest is located/feeding. For example, as microbials act slowly, targeting of late instar lepidopteran pests is unlikely to be effective as they will cause significant damage before they succumb to infection. If target substrate (e.g. soil), crop architecture or product formulation do not provide sufficient protection against UV radiation, sprays should be applied in the evening. As microbials are particulate, it is possible that application at low concentrations and with small droplets will result in many spray droplets not containing any or insufficient numbers of the pathogen, thus spray rates/volume given on the label must be strictly adhered to. If the same equipment used for application of microbials is also used for application of chemical pesticides, a thorough cleaning (decontamination) of the equipment is required before it is used for microbials. Although generally true for all pesticides, tank mixes should be avoided unless the label specifically states otherwise, or expert advice/information confirms this is possible. Because they are very specific and work slowly, it's often tempting to combine products. However, some combinations can work against each other. For example, pairing a synthetic chemical pesticide that halts insect feeding with a microbe that needs to be injected could be antagonistic. Also, some combinations might directly harm the microbes, like mixing fungicides with fungus-based products. Most microbials are highly UV sensitive, so application during times of high UV irradiation should be avoided. Fungi should preferably be applied when humidity is high to improve the likelihood of good germination (although an oil-based formulation can circumvent this requirement). Obviously, no application should take place during precipitation. The rainfastness of the product must be determined, as this will differ between products and crops.

Some microbial agents have been registered as seed treatments, such as Bacillus spp. against pathogens, such as nematodes and pests such as aphids, cutworms, wireworms, and nematodes.
There have been examples of field resistance to bacteria and viruses, so continued use of single strains should be avoided. Application to initiate an epizootic can be considered to suppress populations over time - rapid impact cannot be expected.

Safety

Human

Basic PPE should always be worn (see CLI PPE guidelines) as formulation additives may have some toxicity or be an eye or skin irritant. Also, when spraying, the applicator should avoid walking into the spray cloud (and bystanders should not be subject to contamination) as, although generally non-toxic, it is possible that the microbe may cause an allergic reaction.

Environment

Contamination of waterways and the environment should not cause a problem but should be avoided as good practice. Due to the specificity of most microbial pesticides, beneficial insects are not directly harmed, although parasitoids may be prevented from completing their life cycle in an infected host.

Waste management

Containers should be recycled through a dedicated recycling programme, in the same way as chemical pesticide containers (see CLI guidelines). If there is not an operational programme, they should be disposed of safely, through appropriate waste disposal systems.

Depending on the formulation, unused/obsolete products are unlikely to pose a hazard. However, it is recommended that they are disposed of through an obsolete pesticide collection and disposal scheme or if not available as hazardous waste. Diluted product can normally be composted.

Botanicals

Challenges/unique properties

Botanicals can generally be regarded as low-toxicity chemical pesticides. In the environment, they rapidly break down due to exposure to ultra-violet radiation and high temperatures. They can break down, including by photodegradation (in the presence of oxygen), high temperatures and the action of some microorganisms. Thus, the activity of unformulated, natural pyrethrum is lost within a few hours.

Transport

Like all pesticides, botanicals should be transported separately from food, feed, and other household items. They should not be put in direct sunlight or subject to high temperatures.

Storage

Similar to transportation, botanicals should be stored separately from food, feed, and household items, out of sunlight and avoiding high temperatures (moderate room temperature is fine). Storage times should be on the label but should be minimized. Due to the possibility of rapid degradation, once a container is opened the product should be used as soon as possible – this means that only enough product that is needed immediately should be purchased.

Application

The majority of uses rely on spray application to the crop, although several products are used to combat storage pests. Due to the possibility of rapid environmental degradation, the product should be applied when the target pest is present in the susceptible stage and to where the pest is located. This is not necessarily the case when using the product to protect against storage pests. For insect pests application should be against young stages to allow time to work.

Safety

Human

Commercially available botanical pesticides have low to moderate toxicity (others, like nicotine, are highly toxic and should not be used), thus basic PPE should be worn when using the product (see CropLife International PPE guidelines for chemical crop protection products, as well as the instructions for each product).

Environment

Although generally of low environmental impact, botanicals may be detrimental to non-target organisms and therefore care should be taken to avoid contamination of waterways and non-crop areas and applications should be timed to avoid pollinators.

Waste management

Containers should have been properly triple rinsed, dried and disposed of in the same way as synthetic chemical pesticide containers, preferably through a dedicated empty pesticide container management programme, or if not available via an appropriate waste disposal system.

Due to their low toxicity and rapid degradation by soil microorganisms, small amounts of unwanted and obsolete botanical pesticides can normally be composted. Large volumes and moderately toxic products should be disposed of through an obsolete pesticide collection system or a general hazardous waste collection system.

Semiochemicals

Challenges/unique properties

All semiochemical-based control technologies should ideally be employed on an area-wide basis, rather than just to individual cropping areas, contrary to the norm for an insecticide application. Additionally, technologies based on semiochemicals tend to work best when pest density is low, meaning they are most effective against low levels of pests. Consequently, treatment should usually be initiated early in the season, while target pest levels are still low. If the semiochemical used in the control technology is the same as that used in traps for monitoring, then trap shutdown is likely to occur. Traps will therefore no longer be reliable in indicating pest levels in the area. Lastly, temperature can affect pheromone release rate. At cooler temperatures or cooler times of the year, pheromone release might not be sufficient for optimal control of the pest. If the adult stage of the pest is nocturnally active, it is nighttime temperatures that are important.

Transport

Generally, no special transportation requirements are necessary, other than that the supplier may prefer that such products are transported cool, to minimize release of semiochemical from dispensing devices. This is also something that should be minimized by the packaging. However, it would be wise to still transport product according to the relevant guidelines provided by Croplife International.

Storage

Most semiochemical-based products have an extensive shelf-life, as long as they are tightly sealed within packaging to prevent release of the semiochemical. Products should also generally be kept cool, preferably refrigerated, to further reduce any release of the semiochemical from the dispenser.

Application

Mating disruption

The larger the area treated, the more effective the treatment will be. This is because there will always be an edge effect i.e. individuals that mate outside of the treated area can still enter the treated area and lay viable eggs, leading to crop damage, particularly in the periphery of the treated area. Applying mating disruption on an area-wide basis will minimise this phenomenon. The pheromone dispensers should also be applied at a density determined to indeed achieve mating disruption, whether by competitive or non-competitive means. Deployment of mating disruption dispensers is therefore often quite labour intensive, particularly where one or more dispensers must be hung per plant and if a tree crop is being treated, where dispenser height is not reachable by hand. However, some mating disruption products are in a flowable micro-encapsulated form and therefore sprayed onto the crop, or supplied in the form of aerosol puffers, at a low density per unit area. The flight behaviour of the target pest must also be considered. For example, it will not help if dispensers are hung lower than the flight level of the pest, or lower than the top of the crop, if the pest generally flies above crop height, as pheromone is often denser than air and will thus mainly volatilize downwards. For the same reason, mating disruption may be less effective where a crop is planted on a slope, as pheromone would move mainly downhill, leaving the higher planted portion of the crop less protected.

Attract and kill

In attract and kill technology, the semiochemical source will not disrupt but will attract the insect, usually being the male insect attracted to a synthesised female pheromone source. This will usually be impregnated with a toxicant, but sometimes a sterilant, which will affect the insect on contact. As with mating disruption, the density of the source must be sufficient to not only attract all of the target individuals in the environment but must be sufficiently attractive to outcompete the attraction of other insects in the environment.

Mass trapping

The concept of mass trapping is similar to that of attract and kill, except that insects are trapped, rather than killed on contact with the pheromone source. Insects will be retained in the trap, either by trap design, a sticky substrate, or a volatile toxicant, such as dichlorvos. The advantage of mass trapping is that one can quantify the number of target pests being affected and the decline in presence of the pest over time.

Safety

Human

Semiochemicals, specifically parapheromones, produced for managing (monitoring and controlling) insect pests in agriculture, are generally safe to the user. Exposure to high densities of pheromone in an enclosed environment with no ventilation could result in olfactory discomfort and headaches. However, this is not representative of a realistic use situation, as pheromones are usually protected within dispensers and are released slowly at extremely low quantities. Thus, before deployment in the field, pheromone dispensers should be kept in sealed packing, preferably refrigerated. Gloves should be worn when handling dispensers and eye contact should be avoided. If there is accidental skin contact, then one should wash the contact area with soap and water. Traps used in attract and kill should not be opened, as they contain pesticides or other substances that may be toxic and precautions taken with attract and kill target sites should be the same as for handling concentrated chemical pesticides.

Environmental

Some pheromones may have high toxicity to aquatic invertebrates and moderate toxicity to fish, but there should be no toxicity to birds and mammals. In the form in which pheromones are deployed for pest management in agriculture, they will have no detrimental effect on beneficial arthropods and are therefore highly IPM-compatible.

Waste management

After expiry, dispensers may be left hanging in the field, as any residual release of pheromone could help augment the efficacy of a new batch of dispensers. However, at the end of the growing season, all dispensers must be removed. On removal of dispensers, these must be disposed of according to local regulations. If there are none in existence, then they should be disposed of in a manner that prevents use thereafter for any other purpose. The same goes for the dispenser packaging. Attract and kill traps and targets should be disposed through a hazardous waste program.

Insecticidal soaps and oils

Challenges/unique properties

Activity of soaps and oils is usually purely on contact i.e. there is no residual action. Consequently, spray coverage is of paramount importance.

Transport

Products are in liquid formulation and are transported in a conventional manner, without the need for extreme precaution associated with the transportation of toxic chemical pesticides. However, for good management, the relevant Croplife and product label guidelines for pesticide transportation should still be adhered to.

Storage

Although generally safe, insecticidal soaps and oils must nonetheless be safely and securely stored in the same manner, as prescribed by the relevant Croplife and product label guidelines.

Application

Both insecticidal soaps and oils are sprayed in aqueous solution, like conventional chemical insecticides. As oil and water are not easily miscible, good agitation in the spray tank is essential. Failure to achieve this may not only compromise insecticidal efficacy but may also increase the possibility of phytotoxicity. Oils are often formulated with an emulsifier, to improve emulsion in water in the spray tank. However, if the oil product is left standing for a while, the oil and emulsifier could separate from one another. Thus, gentle agitation of the oil might be required before adding to the spray tank.

Soaps and particularly oils must be sprayed at the appropriate and recommended phenological timing in the life of the crop plant in order to avoid either acute or chronic phytotoxicity. Acute toxicity could be in the form of burn or leaf and fruit drop; chronic phytotoxicity could be in the form of reduced yield. Spraying should also not be conducted when temperatures are too hot and especially humidity too low, as this may result in undue stress to the plant. Label instructions should specify these parameters.

A few oils have a degree of toxicity to the target organism, such as Neem oil. However, most oils and soaps have purely a physical killing action on the target. Oils prevent gas exchange through egg membranes, clog insect mouthparts and deter feeding and egg laying. Soaps are fatty acids that can degrade or dissolve the protective layers of the insect cuticle, causing the insect to desiccate. Results from the application of soap are usually seen in 1–3 days. Multiple applications are often needed to be effective. Both soaps and oils are effective for managing soft-bodied insects like aphids, scales, whitefly, mealybugs, thrips, and spider mites. Due to their physical action, coverage of application must be absolutely thorough, ensuring that the spray is deposited exactly where the pest infests the crop. If this is not achieved, efficacy will be compromised. However, where this is indeed achieved, efficacy may be equivalent to that achieved with an effective chemical pesticide.

Safety

Oils and soaps are mostly of low toxicity. However, some oils with a high dimethylsulfoxide (DMSO) level may be categorised as carcinogenic, mutagenic, or toxic to reproduction (CMR) by the Globally Harmonised System of Classification and Labelling of Chemicals (GHS). Although usually safe, basic PPE is still recommended during the mixing and application of insecticidal soaps and oils, as per the relevant Croplife and product label guidelines. This includes clothing that covers both arms and legs, closed shoes and gloves. During spraying, a mask, hat, and eye protection are also advisable.

Waste management

Dispose of empty triple-rinsed containers as non-hazardous waste or preferably collect through a container recycling programme. Obsolete stocks or expired product should be disposed of through an obsolete pesticide collection system or an appropriate waste collection system (depending on GHS classification and local regulations: hazardous or non-hazardous waste), if available.

Fermentation products

Challenges/unique properties

Although many of these products have low mammalian toxicity, some, such as abamectin are classified as highly hazardous. Generally, the unformulated products are sensitive to high temperatures and sunlight, but in the absence of sunlight are stable for several months.

Transport

In common with synthetic chemical pesticides, fermentation products should be transported separately from food, feed, and household items and not subject to direct sunlight and/or high temperatures.

Storage

Fermentation products should be stored, in their original, labelled container separately from food, feed and household items, preferably in a locked or secure store. They should not be stored in direct sunlight or under hot condition (store at room temperature or below).

Application

Fermentation products are either applied as a spray or incorporated into baits. If applied by spray, the application should be timed for when the susceptible stage of the pest is present, as the products are degraded in sunlight in a few days. Degradation is slower when incorporated in baits. Baits and traps containing baits should be placed in the area where the pest is located.

Safety

Handling and safety precautions should be the same as when using synthetic chemical pesticides. This basic PPE should always be worn and when spraying the applicator should not walk into the spray cloud i.e. apply downwind, to the side.

Waste management

Waste management should be the same as for synthetic chemical pesticides. Triple-rinsed empty containers should be disposed through a dedicated container management programme, if available, or through an appropriate waste disposal scheme. Unwanted and obsolete product should be disposed of through an obsolete pesticide collection scheme or, if not available, through a hazardous waste disposal system.

Counterfeit and illegal Products

In common with chemical products, counterfeit and illegal biologicals threaten to undermine safe and effective pest management. Counterfeit products are fake or adulterated copies of the genuine product. Examples could be a Bt product using an unknown or untested strain of Bt or a baculovirus product to which a synthetic chemical pesticide has been added without proper testing or registration. Illegal products are those that are not registered or approved by the authorities in the country where it is sold.

These products have unknown quality, efficacy, and safety profiles and normally unlawful to use. To avoid unknowingly using counterfeit or illegal pesticides, products should only be purchased from reputable dealers, who should normally be licensed to sell crop protection products. Products offered by a non-authorized dealer, on the street or sold directly from a truck should not be purchased. Where relevant the product should be registered. For macrobials, registration is not generally required, but they should be approved in the country of use and evidence of efficacy against the target pest should be requested by the purchaser. Tips for recognising counterfeits and illegal products include:

- The price of the product is significantly lower compared to the original
- The label is not written in the local language and/or shows mistakes in grammar and spelling
- The logo/trademark and, if present, hologram on the container or label look different from the original
- The shape of the container is different from the original
- The container is not properly sealed
- The cap on the container is different from the original
- The seller refuses to provide a proper invoice for the purchase

2 USE OF BIOLOGICALS IN IPM STRATEGIES

Over the years, numerous definitions of IPM have been proposed. However, where these are indeed accurate and true definitions of IPM, they all share the same criteria. For the sake of uniformity, we choose to use the definition adopted by the Food and Agriculture Organisation of the United Nations (FAO), which states: "Integrated Pest Management (IPM) means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM promotes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms."

Origin, history, and evolution of IPM

The concept of Integrated Control was the forerunner to IPM. It arose in the late 1950s in response to environmental concerns and the realization that the approach to chemical control needed to facilitate biological control. Integrated Control was very simply defined as "Applied pest control that combines and integrates biological control and chemical control." It consisted of two aspects: economic damage levels and their associated economic pest thresholds. As this approach developed in the 1960s, it was realised that pests could be managed, rather than just controlled, paving the way for the introduction of IPM. The term Integrated Pest Management was first used in agriculture during the 1970s. As can be gathered by reviewing the FAO definition of IPM and other definitions, this was a far more complex and multi-faceted approach than the Integrated Control approach of the 1950s.

Explanation of IPM

There is a series of components within IPM, that are integral to IPM as an approach to pest management:

- The use of different techniques. These would fall into the categories of biological, cultural, and chemical control. These are defined and explained in detail below.
- The harmonious combination of these different techniques. They must be used in a compatible fashion, so that no one technique undermines or precludes another. The most obvious example is avoidance of the use of a long-residual, broad-spectrum chemical pesticide, which could be detrimental to effective natural enemies used for biological control (biocontrol).
- The programme must be flexible. It should be specifically appropriate to the situation in each cropping area at that time during the growing season. There is no one-size-fits-all. Based on specific real-time monitoring data, situationally specific pest management decisions will be made, which can differ from field to field and season to season.
- The programme must be ecologically sound. There should be minimal detriment to all environmental factors, except to the pests themselves.

- The programme must make economic sense. A true IPM programme eliminates unnecessary pest control actions, through intensive monitoring and decision-making based on pest thresholds, and should thus be more cost- and time-effective and affordable.
- Long-term control of pests should be achieved. Control must be sustainable. This is achieved through preservation of effective natural enemies, which suppress pest populations, ensuring that these natural enemy levels are not disrupted through injudicious use of chemical pesticides.

There is also often a misunderstanding that the emphasis within IPM lies on the "integration." However, the emphasis should be on the "management." Management implies understanding and this understanding can only be acquired through the collection, interpretation, and use of specific, accurate and relevant data. This is the bottom line of IPM. Consequently, calendar-date scheduled application of pesticides must be avoided as far as possible.

Why IPM?

Benefits of IPM

- IPM is the most sustainable approach to pest management, as the balance between natural enemies and pests is not disrupted.
- Secondary pest outbreaks will be avoided. A secondary pest outbreak is the resurgence of a non-target pest, which occurs when broad-spectrum long-residual pesticides are used to control a primary pest, but afterward, a formerly insignificant pest replaces the target pest as an economic problem.
- Chemical residue problems should be avoided. As less chemical spraying occurs within an IPM programme and products with a short residual efficacy should be preferred, the risk of exceeding a permissible maximum residue level MRL is reduced.
- IPM incorporates good pesticide resistance management. This is a result of fewer pesticide applications, particularly chemical pesticides, and alternating products with different modes of action. Additionally, biopesticides are generally less prone to pests developing resistance to them.
- IPM is an environmentally responsible approach. As less use is made of broad-spectrum long-residual chemical pesticides, there is less detrimental impact on the environment in general, including all forms of animal and beneficial insect life. Furthermore, as inter-row vegetation and conservation landscaping are encouraged, a more favourable ecosystem for diverse species, including beneficial insects, is created.
- IPM can aid in the management of phytosanitary pests. These are pests for which markets have zero tolerance, due to their absence in those regions. Contrary to orthodox wisdom, a persistent chemical pesticide programme may not be the best approach. Preservation of effective natural enemies may well be more effective. These can continue to suppress the pest population after residual efficacy of pesticides has expired and can continue to be effective late into the growing season when thorough

application with pesticides becomes more difficult due to the density of the crop canopy.
- Reduced pesticide application should lead to significant cost savings and thus increased profit margins.

Benefits of IPM

While there are numerous benefits to adopting an Integrated Pest Management (IPM) approach that could persuade a farmer it's in their best interest to use such a method, there are also specific factors that compel farmers to do so, such as:

- Stakeholders increasingly want assurances that chemical pesticides are only used when absolutely necessary and are used safely and sustainably.
- There is a steady reduction in official MRLs for numerous active ingredients and in residue tolerance in general, leading to the withdrawal of availability of many chemical pesticides or the unacceptability of their use for certain markets.
- Retailers often ignore scientifically determined safe MRLs and impose their own arbitrarily determined MRLs at a much lower level. This makes the use of certain pesticides impossible and thus forces farmers to consider alternative modes of control, such as biopesticides.
- Consumer demand for chemical-free or organic produce is growing.
- National and international environmental regulations are driving a reduction in chemical pesticide usage and greater adoption of IPM in farming.

Detailed explanation of components of IPM

Biological Control

Biocontrol, supported by cultural control practices, should be regarded as the first option within an IPM programme.

Cultural control

Cultural pest control refers to agronomic and mechanical practices that manipulate the environment and crop production system to reduce or eliminate pest populations. Cultural control practices can range from simple concepts such as adjusting planting dates to avoid pest infestations to more complex ecological approaches that may include adjusting the spatial and temporal arrangement of an agroecosystem. There are a number of practices within the agricultural environment that can be classified as cultural contributions to the control of pests. Here we list some examples.

Pest avoidance

One of the most commonly and easily implemented cultural pest management practices, particularly with annual cropping systems, is the concept of avoidance. Practices such as adjusted planting dates and crop rotations can be used to avoid pest infestations. Avoidance measures can be particularly effective when implemented on an area-wide scale. Implementation of crop-free periods can also be used to reduce pest levels.

Conservation landscapes

Although considered a form of cultural control, the preservation of conservation landscapes adjacent to, between and within agricultural plantings, can enhance conservation biocontrol. Occurrence of natural enemies of agricultural pests can be enhanced by managing habitat to provide key resources in and around farm fields. In particular, vegetation diversity may help ensure temporal resource continuity so that natural enemies are less likely to experience detrimental gaps or bottlenecks, as they move through and use different habitats. Continuity of trophic (food) and structural (shelter) resources affect natural enemy conservation and pest control outcomes within farm fields and across agricultural landscapes. Key trophic resources include alternative prey and non-prey food (such as floral nectar and pollen), which can bolster natural enemy nutrition when pests are scarce. Vegetative and non-vegetative structural resources can protect natural enemies when crop fields are disturbed and provide important overwintering habitats in temperate regions.

Ground cover vegetation

The conservation of or even active planting of inter-row ground cover vegetation within agricultural plantings will have a similar effect as described for conservation landscapes, but on a smaller and less protected scale. Ideally, one would want plants that not only provide protection to natural enemies and an enhanced micro-climate, but also an alternative food source. However, this is dependent on what plants are suited to the specific environment and how specific the natural enemy food preferences are.

Push-pull strategy and intercropping

The push-pull strategy makes use of volatile plant compounds to influence insect behaviour. Volatile compounds produced by plants are used by insects to identify and locate potential food and breeding plants. Non-host plants (e.g., aromatic plants) can be used to create insect repellents, anti-feedants, or insecticides because they release volatiles with repellent or deterrent properties in response to an attack. Intercropping with plants that can kill or repel pests or attract natural enemies, can be another useful cultural practice in enhancing IPM.

Alternative host removal

Polyphagous pests, particularly indigenous pests, may have several host plants, other than the crop on which they are a pest. Where these plants grow within or adjacent to the cropping system, they can serve as a source of inoculum for the pest to enter into the crop. Removal of such alternative hosts may assist in reducing pest pressure in the general area. Harvesting or reaping of nearby alternative host crops may also trigger a pest migration into the crop in question.

Ant management

Ants are recognized as being potentially highly disruptive to the natural enemies of sap-sucking insects that produce honey dew. Ants not only stave off parasitoids and to a lesser extent predators, but their mere presence can have a non-consumptive disruptive effect on natural enemy efficacy, decreasing the efficiency of the natural enemies. However, as detrimental as ants can be to biological control, when present within the crop itself, so too can they be highly effective natural enemies of soil-dwelling life stages of pests, when restricted to the soil environment within an agricultural field. This includes preying on arboreal pests that pupate in the soil, such as many lepidopteran and fruit fly pests. Consequently, the best approach is not to kill the ants, but to restrict their access to the plant itself. This can be achieved a lot more easily with trees than shrubs or grasses, as trunk barriers can be used on trees.

Physical barriers

These can be used not only to exclude ants from the crop, but also other flightless arthropod pests that have a soil-dwelling life stage, snails, slugs, and rodents. An increasingly popular physical barrier is the use of nets. The main purpose of nets is to protect agricultural crops from sunburn, wind, and hail, but in some instances, are also effective in excluding or reducing the occurrence of insect pests. Nets can either be incomplete exclusion netting, including tunnel and drape netting, where nets are removed at harvest time. The second type of netting is full canopy or exclusion netting, where permanent structures are erected over the entire crop.

Varietal selection

Certain varieties of agricultural crops may be more tolerant of or even resistant to some pest species. These can be appropriated through selection of an existing tolerant or resistant variety, through breeding or genetic engineering.

Mulches

Reflective mulches have generally been used to manage the spread of insect-vectored plant diseases, such as aphid-vectored viruses in vegetable crops and psyllid transmitted Liberibacter in citrus. Mulches, which are usually aluminium-based, reflect ultraviolet light and repel incoming insects, preventing them from landing on the crop plants.

Opaque plastic sheeting on the soil surface can also be used to control soil-inhabiting insect pests, plant-parasitic nematodes, soil-borne fungal pathogens, and weeds, mainly through solar heating.

Chemical control

Product selection

Theoretically, no chemical active ingredient is precluded from consideration in an IPM programme, as long as its use can be justified as effective, with manageable risks. The most IPM-compatible chemistry is that which either is narrow spectrum and short residual or has been demonstrated to have minimal effect on important natural enemies in non-target effect bioassays and field experience. Seed treatments and certain systemically applied products can also be beneficial in suppressing pest levels before natural enemy levels have responded to the pest, also with minimal effect on natural enemies.

Timing of application

Sometimes the damage potential of a pest is so severe that it is necessary to control it immediately. However, where some flexibility is possible, application of chemical sprays should be timed to have as little impact on natural enemies as possible. In certain cropping systems, spraying early in the season, while pest levels are low, but still basing such decisions on monitoring and threshold exceedance or established predictive methods, is often not only more effective in controlling the pest, but also less disruptive to natural enemies. Natural enemies will not yet have built up to effective levels and there may be several months to harvest during which time this can happen, and the relevant pest can be adequately suppressed. However, in other systems, biocontrol can be effective early in the season and can be used to prevent early build-up of pests and only when this fails, should chemicals be used. Chemical sprays, known to be deleterious to parasitoids, can also be made when it is known that the majority of parasitoids are protected in the larval or pupal stage, within the host, assuming that they are indeed endoparasitoids.

Non-target effects

Several studies have been conducted on the non-target effect profiles of pesticides against important natural enemies, and there is therefore both peer-reviewed published data and unpublished databases, such as those from the IOBC and various biocontrol agent manufacturers, which can be consulted. Consequently, educated decisions can be made on product selection.

How to implement IPM

Data collection for decision-making

One of the cornerstones of a successful IPM programme is the regular collection of accurate and reliable data. Without this, it becomes impossible to make an educated decision, whether to apply a control measure or to withhold from applying a control measure, the latter being an even more important decision in the maintenance of an IPM programme. These data are collected in various ways, at regular stages throughout the growing season and even prior to the start of the season and at harvest time. Data should always be stored in a user-friendly fashion so that it can be revisited at any time, including in subsequent seasons, when one can look back and be reminded of lessons learned. In order to make the decisions on whether intervention is necessary against a particular pest and what sort of intervention is necessary, the data are interpreted using action thresholds.

At harvest inspections

The first step towards generating data to assist with decision-making within an IPM programme, may be collected at harvest during the previous season. This will depend on whether the crop and pest in question would experience a carry-over from one season to the next and is likely more applicable to perennial than annual crops. The crop is systematically inspected for pest infestation and damage. This should be done on a representative sample of the crop and preferably before harvest. This is because if such an inspection is conducted after harvest, it cannot be known how representative the sample is of the crop as a whole. It could be the produce from one particular section of the field that could either under or over represent the damage/infestation in the field as a whole. Secondly, during harvesting, produce that is particularly badly damaged or infested may be left behind in the field, thus excluding valuable data from the survey.

Pre-crop set inspections

These inspections are relevant to perennial, but not annual crops. Once the produce has been harvested and the crop plant is more open and accessible, especially if it is a crop that is pruned in winter, inspection for pest presence on the whole plant becomes easier. Furthermore, in moderate climates, pests can begin to build up during late winter and spring. Consequently, it is important to inspect the plant during winter and to inspect the new flush and blossoms during spring, for any pest presence.

Trapping: pest and natural enemy monitoring

Once the new growing season has begun, several pest species can be effectively monitored through the use of trapping systems. These are often pheromone traps, where synthetic sex pheromone lures exist for the species in question. They could also be food bait traps, coloured traps, or light traps. Traps differ in their reliability and must therefore be understood in the context of the pest and crop in question. There may be a reasonable correlation between trap catches and crop infestation and damage, or traps may be no more than an early warning that the pest is present and that intensified scouting on the crop itself is justified. Traps can also be used for monitoring natural enemies. However, this is usually as a by-product of monitoring for the pest, often with coloured sticky traps.

Scouting for pests, diseases, and weeds

Scouting entails visual inspection of the plant part that the pest or disease in question infests/infects. This could be the stem, the leaves, the blossoms, or the produce itself (e.g. fruit, nut, boll, head). Frequency of scouting should be based on the damage potential of the pest or disease and how rapidly it can build up to a damaging level. Thresholds will not only be specific to each pest and disease, but also crop and region specific. Consequently, these should be acquired from a local expert or guidelines manual. It is rarely necessary to scout more frequently than once a week. The scouting sample size must be calculated to be sufficiently large for the area being scouted, with a sufficiently high level of statistical confidence. The scouting route must also be sufficiently representative of the field as a whole. Practical designs are to scout diagonally across the field, or in a V or even W shape, if the field is particularly large. Scouting for weeds is generally conducted in a less structured fashion.

The scout must have 20/20 vision, must be well-trained and must be equipped with a good magnification tool, such as a magnifying glass. The scout needs to identify pests, natural enemies, weeds, and plant diseases (as opposed to nutrient deficiencies). The scout must also record all data collected, using a fit-for-purpose recording form or App, if such is available. Strongly consider marking data plants and thus using the same plants throughout the season. This will provide a greater degree of confidence that any change in pest levels is a genuine change and not just because different plants are being used. However, in addition to the data plants, spot scouting elsewhere in the field can be conducted, in case there are pest outbreaks in patches in the field that are outside of the scouting path.

Scouting helps with three forms of decision making: a) it assists with immediate decision-making, where tolerance thresholds exist for the pest; b) it assists with seasonal decision making, where for example natural enemy build-up should lead to a decline in pest level after a certain stage in the season; and c) it assists with decision-making from one season to another, by being able to make comparisons and learn from previous successes and failures in decision making.

Scouting for natural enemies of arthropod pests

For an even higher level of accuracy in one's decision-making, monitoring of natural enemy activity should also be conducted. For some pests, such a procedure has been formalized through establishment of a relationship between the presence and activity of the natural enemy and the damage caused by the pest. This could be fairly simple; for example, the mere observation of conspicuous predator or parasitoid activity may be sufficient to convince the decision-maker that the application of a treatment for the pest is probably not necessary. It could also be slightly more complex, for example, it could be determined that a certain minimum level of infestation by predatory mites, measured as average number of mites per specific plant part, is required in order to have a significant impact on the target pest, such as a thrips or mite pest species. However, this could also be very complex; for example, it may be necessary to determine multiple factors in order to make an educated decision on whether natural enemy activity is adequate or not. This could include pest infestation level, pest life stage, mortality rate of the pest, percentage parasitism of the pest, parasitoid species involved and duration remaining until start of harvest. Very few farmers will have the skills, time, and knowledge to make such a decision and will therefore require the services of an expert entomologist.

Microscopic inspections

Microscopic inspections can very often help with natural enemy surveys. If parasitoids are very small and if it is difficult to determine whether a pest is parasitized or not, for example in the case of some scale insects, collection of a representative sample from the field and microscopic inspection thereof, can add valuable additional information towards being able to make a good IPM decision. Microscopic inspections will enable one to accurately determine level of pest mortality, level of parasitism, parasitoid species and any other factors that might either add to the level of biological control, such as signs of host feeding, or might detract from the level of biological control, such as the presence of hyperparasitoids.

Summary of requirements for data collection and interpretation

In order to successfully implement an IPM programme, certain tools and expertise are recommended. These can be summarised as follows:

- A well-trained pest monitor/scout
- A handbook or App for pest and natural enemy identification
- A hand-held magnifying glass and/or magnification head-loop
- A tailor-made form or App for recording pest and natural enemy infestation/presence
- Designed for purpose traps for relevant pests, where such are available
- A list of intervention thresholds for the various pests (and natural enemies)
- A stereo (dissecting) microscope, with a magnification of around 50 X
- A list of the IPM ratings of the various pesticides available. This could be in the form of non-target effect data against key natural enemies
- The services of an expert consultant, who is an expert in IPM implementation
- Courage!

All of the above may not be available to the grower, depending on socio-economic constraints, but simple field monitoring of pest and natural enemy levels and use of action thresholds is essential to IPM implementation.

Data interpretation and decision making: Intervention thresholds

For certain pests, the relationship between the level of pest presence and the damage caused has been determined in dedicated applied field studies. This could be the pest presence as determined by a trapping system or through visual scouting for the pest on the crop itself. If the pest causes cosmetic damage or crop loss, then the threshold determined will usually be an economic one. For such pests, there can almost never be zero tolerance, as the cost of an intervention must be weighed up against the value of losses due to damage or crop reduction by the pest. The level of damage that can no longer be tolerated and justifies the cost of applying a treatment (economic damage level) is related to the level of pest occurrence that can cause such loss. The action threshold should be set to avoid economic threshold exceedance.

If the insect is a pest due to it vectoring a disease or if it has a phytosanitary or quarantine status on an export crop, the intervention threshold will very likely be a lot lower than that determined for cosmetic or production pests. In other words, a far lower level of pest presence can be tolerated before action is justified. This level may even be as low as the mere presence of any pest individuals. This scenario may be unavoidable, due to the devastating nature of such pests. However, it often does not lend itself well to IPM implementation, unless there is a comprehensive suite of biological, biorational and appropriate chemical pesticides available for the control of the target pest.

IPM and Resistance Management

Resistance to pest control agents (chemicals and biologicals) can develop over time when pesticides with the same mode of action are repeatedly applied in the same area/season. Resistance occurs when a pesticide exhibits reduced effectiveness or no longer controls the pest population at the formerly effective rate. One of the many benefits of IPM is its contribution towards resistance management. Resistance management is not necessarily a part of IPM, but as IPM lends itself towards less spraying, the likelihood for development of resistance by an insect pest to a particular active ingredient should be significantly reduced. IPM also promotes the use of different products, with different modes of action, which reduces the possibility of resistance development. As IPM entails a high level of educated decision making in the management of the relevant pest complex, the addition of a resistance management strategy to this decision-making is sensible. Furthermore, more biopesticides will be used and although resistance to biopesticides is not impossible, it is less likely than with chemical insecticides. For more information on resistance management see CropLife International guidelines and its references to the Resistance Action Committees

What the future holds

Drivers of IPM

IPM implementation and thus the use of biologicals is set to increase dramatically in the future. The biologicals market has grown at a rapid rate in the past 20 years or more, far exceeding the growth in pesticide usage in general. Pressure to move away from conventional pesticide usage towards a biointensive IPM approach is already being imposed by regulators, consumers, retailers, environmental lobbyists, and society in general over the last number of years and is set to only increase. Agrochemical companies are participating and even leading this initiative to an ever-growing extent.

Technologies and products in the future

Innovation in the biologicals sector has occurred at a rather slow rate, with the introduction of very few novel organisms and technologies over the years. As biologicals become more mainstream in agricultural pest and disease management, greater investment should increase novel innovation. The range of organisms and compounds developed as biologicals may just be the tip of the iceberg of what is available and with increased bioprospecting, an array of novel options may soon be discovered and developed. Genetic selection and modification may also play a greater role in the parts of the world where the latter is an accepted technology. Effective formulation of biologicals has also lagged behind that of chemical pesticides, and this too should improve dramatically in future, leading to products with better and more protracted field efficacy.

Abbreviations

Bt	Bacillus thuringiensis
CLI	CropLife International
CMR	Carcinogenic, mutagenic, or toxic to reproduction
DMSO	Dimethyl sulfoxide
EPF	Entomopathogenic fungi
EPN	Entomopathogenic nematodes
FAO	Food and Agriculture Organisation of the United Nations
GHS	Globally Harmonised System of Classification and Labelling of Chemicals
GV	Granulovirus
IOBC	International Organisation for Biological Control
IPM	Integrated Pest Management
MD	Mating disruption
MRL	Maximum Residue Level
NPV	Nucleopolyhedrovirus
PPE	Personal protection equipment
RNA	Ribonucleic acid
RNAi	Ribonucleic acid interference
SIT	Sterile Insect Technique
spp.	Species (plural)
USD	United States Dollars
UV	Ultraviolet

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