MICROBIAL INSECTICIDES AND IPM: CURRENT AND FUTURE OPPORTUNITIES FOR THE USE OF BIOPESTICIDES

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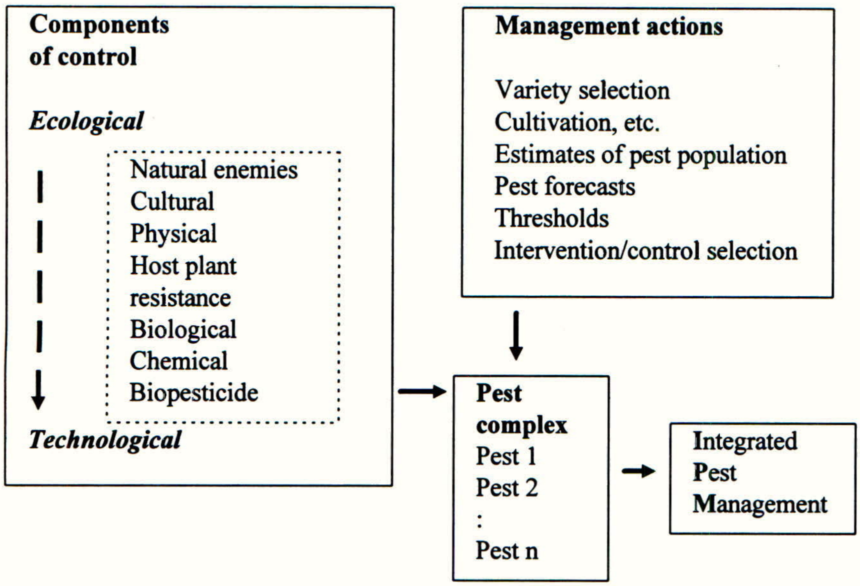
ABSTRACT

Integrated pest management systems have developed so that at one end of the spectrum they can be defined as 'ecological' and at the other as 'technological'. Biopesticides are necessary as components in IPM systems to overcome the limited availability of effective chemical insecticides on some commodities and to benefit policies aimed at reducing chemical pesticide usage. The development of biopesticides has been limited by the relatively small commercial opportunities they afford and difficulties encountered making a direct comparison of performance between the two products. Several examples are described whereby biopesticides could be effective in IPM systems. The future of these exciting products is likely to take an increasingly technological route unless there are radical changes in the regulatory requirements of pest control products.

INTRODUCTION

The majority of crops, be they perennial orchards or plantations, annual field crops or high value crops grown under protection, are damaged by one or more insect or mite pest. It has been accepted theoretically that control of pest complexes can only be achieved by the integration of a diversity of compatible components aimed at suppressing pest populations below acceptable thresholds (Stern *et al*., 1959). Many of the successful systems of integrated pest management (IPM) adopted throughout the world rely ultimately on the judicious use of synthetic chemical insecticides as the mainstay of the control strategy. This is achieved by the adoption of sophisticated sampling strategies, forecasting systems and thresholds, with the overall objective of reducing pesticides usage (e.g. Leslie & Cuperus, 1993). These systems rely heavily on technology and are perhaps only a substitution of the chemical insecticide technologies that precede them. There are, however, a much broader range of control components available to the farmer and practitioner of IPM which include plant varieties resistant to pests, natural enemies, the release of antagonists to achieve biological control through inundative or classical methods, cultural methods including intercropping, rotations and scheduling to avoid pest attack, physical methods of pest exclusion, and, of course, biopesticides. The balance of the components within an IPM system may be given different emphasis which has led Waage (1996) to divide such systems into 'ecological' and 'technological'. In the former, the farmer has control of the decision making through his knowledge of the interaction between the biological components of the system, while, in the latter, technologists, and the availability of capital, take much of the decision making away from the farmer to his advisors. In reality there is a spectrum of approaches to IPM of which the 'ecological' and 'technological' are the extremes (Fig. 1). Biopesticides are included at the technological end of the spectrum as considerable research is directed at their improvement.

Figure 1. Components of control, ranging from 'ecological' to 'technological', and management actions that form the basis of IPM systems (adapted from Waage, 1996).



The objective of this paper is to examine the use of micro-organisms (viruses, bacteria, fungi and nematodes) as biopesticides for insect control, and the constraints on their use, within the spectrum of IPM systems outlined above, with emphasis given to food crops. The instances where individual species are controlled by the application of a single biopesticide to achieve either classical biological control or the long-term suppression of populations, (e.g the control of rhinoceros beetle (*Oryctes rhinoceros*) in coconut in the South Pacific with a non-occluded baculovirus (Zelazny, 1976, Cunningham, 1995) and of the European spruce sawfly (*Gilpinia hercyniae*) in Canada (Balch & Bird, 1944, Cunningham, 1995)), are excluded as this does not fall within the philosophy of IPM outlined above. Similarly, the use of plants transformed with toxins, such as *Bacillus thuringiensis* (*Bt*), will not be discussed.

THE NEED FOR BIOPESTICIDES

Let us first ask the, perhaps, cynical question as to whether biopesticides are needed at all. There is a large and highly sophisticated agrochemical industry investing hugely in the development of new synthetic chemical insecticides to augment the vast array of products already on the market. However, there are a number of circumstances under which these insecticides either cannot be used, or where they provide inadequate control. Conversely, there are cropping systems where the economics of production, and the shortage of resources do not allow intervention with such chemical insecticides. By examining these situations the real opportunities for the uptake of biopesticides within IPM systems can be identified.

Limited availability of synthetic chemical insecticides

Agrochemical industries remain profitable by obtaining a sufficiently large share of a large enough market to recoup their development and registration costs. The primary targets for agrochemical development are therefore the pests of broad-acre crops grown on a large area worldwide. However, in general, it is only the large multinational companies that are able to service these global markets. Niche markets are usually given low priority by these companies unless a product developed for a large market can also be used in these smaller markets. As national pesticide registration regulations demand that each active ingredient is reviewed periodically, manufacturers do not look favourably on the small sales provided by some niche markets and are therefore not supporting the continued registration of some active ingredients. The consequence is that niche commodities frequently have few chemical options available to control pests and so alternatives, such as biologically based products, need to be found. Conversely, there are few multinational companies with extensive interests in biopesticides, with the exception of *Bt*, and so few attempts have been made to tackle these large markets with biopesticides. It has frequently been the smaller companies which do not seek such large returns that have developed biopesticides.

Biological constraints on the use of synthetic chemical insecticides

The widespread use of chemical insecticides has resulted in the development of pest genotypes that are resistant to one or more classes of insecticide. Although many pest species are susceptible to chemical insecticides, high levels of resistance occur sufficiently frequently that chemical options are no longer considered for some pests. Sometimes the chemical insecticide, or at least formulated products, are phytotoxic to the target crop, e.g. to ornamentals and young plants during propagation, thus negating the chemical option.

Chemical insecticides are biologically active compounds which are seldom specific to a single group of pests, despite the efforts of the agrochemical industry to seek such compounds. Increased selectivity to some pests can be achieved by specific application methods, e.g. seed treatment, but such approaches are applicable to a relatively small number of pests. Problems arise when natural enemies of pests, be they naturally occurring or introduced by growers, and other non-target species, are more sensitive to chemical insecticides than the target pest. In some circumstances, e.g. orchard systems, the elimination of these natural enemies can result in greater pest damage in the presence of insecticides, as described by Solomon (1989). These natural enemies are central to the success of 'ecological' IPM systems.

The use of insects to pollinate crops is vital to the economic production of some commodities. For example, commercially-produced colonies of bumble bees are now used to pollinate virtually all long-season tomato and sweet pepper crops grown under protection in north west Europe. This method of pollination is so effective that it is a major driving factor in determining the methods of pest control. Chemical insecticides are incompatible with these pollinators and, therefore, alternative biologically-based control-strategies are demanded during the fruit setting period.

Policies to reduce chemical insecticide usage

Now that food is readily available in developed countries, increasing pressure is being placed on how that food is produced, especially the use of agrochemicals on crops. Pesticide reduction policies in some countries, such as Denmark, have established specific targets to halve the quantities used. Policies on the use of agrochemicals in the UK are shared between the Ministry of Agriculture Fisheries and Food and the Department of the Environment and were published recently in the White Paper, *Rural England - A nation committed to a living countryside* (1995), in which an action plan for the responsible use of pesticides was identified.

Consumers are concerned about food safety, particularly where commodities are eaten directly without further cooking or processing e.g. fruit and vegetables. In the UK, the multiple retailers are becoming increasingly pre-eminent in limiting the use of chemical insecticides while retaining product quality. In the UK protocols detailing methods of growing crops are coordinated by the National Farmers Union, with the cooperation and participation of the majority of the multiple retailers, and are now available for more than 30 horticultural commodities (Anon., 1994, 1995). Such protocols are being applied increasingly to commodities grown world wide.

In summary, there are a range of circumstances in which synthetic chemical insecticides are either not effective or are inappropriate. In these situations there are large opportunities for alternative control methods, including biopesticides.

CONSTRAINTS ON BIOPESTICIDES

Many of the reasons for needing biopesticides have also become constraints on their development and production. Some of these are outlined below.

Commercial constraints

The development of micro-organisms as insecticides is driven by the same commercial considerations as apply to synthetic chemicals; products need to obtain a sufficiently large share of the market to recoup costs and make a profit. Following this argument pests specific to commodities that are grown only on small areas may not be the most suitable targets for biopesticides, unless the production of the micro-organisms is limiting. Producers of biopesticides are interested in repeat sales, and hence repeated applications. Such an approach encourages biopesticides to be used in a similar way to synthetic chemicals, thus perpetuating the 'technological' approach to IPM. A more classical approach to biological control, whereby limited applications of the biopesticide lead to a sustained equilibrium between the pest and its pathogen, provides a more 'ecological' approach to IPM and is of considerable commercial interest to farmers but not to the biopesticide producer, unless he is also the farmer.

Producers of biopesticides can only retain a competitive advantage if the product can be patented. This cannot be done with the wild type pathogens but modified organisms can be patented thus driving the industry round a technological treadmill.

The production of data packages to satisfy the regulatory authorities is a significant development cost, the requirements of which vary considerably between countries. Wild type micro-organisms may be considered either as part of the native fauna and flora and as such do not require registration, or as pesticides because they are applied to crops for the purpose of pest control. These different scenarios, with associated registration costs, impact considerably on the likelihood of biopesticides being incorporated into IPM systems in either highly technological agriculture or where it has very limited resources.

Biological constraints

The ability to integrate a number of different control options in an IPM system demands knowledge of the biological characteristics of both the pest and of microbial agents, particularly their variability, persistence, specificity, rate of kill and reproduction. Methods may be needed to estimate pest populations and forecast the vulnerable stages in the insect life cycle so as to optimise the use of the biopesticides. It is only through knowledge of the biological and ecological interactions between pathogens, pests and the environment that biopesticides will be used in both technological and ecologically based IPM systems. These biological issues are addressed below.

Biological systems are characterised by variability, and it is this very variability in the efficacy of field control that discourages the commercial use of biopesticides when users are expecting the 95%, or greater, control that is achieved traditionally by synthetic chemical insecticides. However, pathogens have not evolved to kill 100% of their hosts; in natural ecosystems it is not to their advantage to do so. The variability of control, is accepted by the regulatory authorities in the UK, but users can be disappointed when biopesticides do not achieve the same levels of control that they have come to expect from synthetic chemical insecticides. The lower rate of insect mortality achieved by biopesticides, compared to synthetic chemicals, emphasises that they are deployed best within IPM systems.

The relatively short persistence of micro-organisms in the environment contributes to the variability in the control achieved by biopesticides. The consequence of this is that high doses of biopesticide need to be applied if sufficient infective units are to remain active for long enough to kill 50%, let alone 95%, of the target population. The persistence of products also has a big impact on their shelf life; in general they can be kept for relatively short periods and frequently have to be kept frozen or refrigerated. The accurate timing of application and accuracy of placement therefore become of prime importance in the effective use of biopesticides.

Specificity has been the characteristic of insect pathogens which environmentalists and practitioners of IPM alike have highlighted as being most beneficial within insect control programmes. Isolates or strains of an individual pathogen species are frequently only sufficiently virulent to be considered as candidates for the control of a single arthropod species. This clearly limits the environmental and ecological risks of their use, but it also limits their commercial potential due to the restricted targets against which they can be used.

Infection of insects occurs by an infective dose of the pathogen or nematode entering the host, either through ingestion (viruses and bacteria) or through the cuticle or other orifices (fungi and nematodes). Subsequently the pathogen reproduces within the host until the insect dies and the micro-organism or nematode is released back into the environment. *Bt* is a little different in that the endotoxins stop insects feeding almost immediately, and epizootics with this pathogen seldom occur in nature. These biological processes, which involve sequential generations of the pathogen, take time during which the insect pest may continue feeding causing further crop damage (Tatchell, 1981). This contrasts with synthetic chemical insecticides which kill, or at least immobilise, their target very rapidly.

Insect pathogens, by definition, require a host in which to reproduce. This may place constraints on their mass production for commercial use; mass production of insects and the pathogens *in vivo* is labour intensive and great care is required to maintain quality. To overcome this considerable effort has been devoted to the development of methods for the *in vitro* production of microbial agents through fermentation or the development of susceptible cell lines which can increase dramatically the quantities of pathogens that can be produced for commercial use.

BIOPESTICIDES IN IPM SYSTEMS

The number of biopesticides that are available commercially throughout the world is relatively small and is dominated by *Bt* products (Lisansky, 1993). There are therefore few examples in which biopesticides are used in true IPM systems. However, I wish to highlight a few examples of programmes where IPM systems are being developed in which microbial control agents have an important rôle. By coincidence these examples are all drawn from horticultural systems in which few synthetic chemical insecticides are registered for use and alternatives have to be found (Tatchell, 1996).

Aphids on outdoor lettuce

Aphids are major pests of lettuce grown outdoors in most parts of the world. In Britain four species are of commercial importance; three infest the foliage and their presence within the lettuce head makes then unsaleable. Such infestations are very difficult to control by biological methods because of the slow speed of kill and nil-tolerance of retailers. In contrast the lettuce root aphid, *Pemphigus bursarius*, feeds on the roots and high populations can cause the plant to collapse and die, but low populations may be tolerated.

Lettuce crops are in the field for only eight to twelve weeks and are planted sequentially through the season to provide continuity of supply to retailers. Superimposed on this is the biology of the four aphid species which indicates that different plantings face a different risk of infestation by aphids. Each planting therefore be treated differently if optimum aphid control is to be achieved. The cryptic habitat on the roots occupied by *P. bursarius* makes chemical control difficult now that no soil-applied insecticides are available for use on lettuce in the UK. The timing of the colonisation of lettuce by *P. bursarius* from poplar trees during a period in July and August each year can now be forecast with some accuracy (Collier, unpublished data) so identifying the plantings at risk. A strain of the fungus *Metarhizium anisopliae* has been identified from the closely related *Pemphigus treherniae* which is pathogenic to *P. bursarius*. The fungus can be incorporated in the modules in which plants are raised for those plantings at risk to provide effective field control of *P. bursarius* (Chandler, 1997). This provides one component of a larger strategy for the IPM of aphids in outdoor lettuce (Ellis *et al.*, 1995).

Caterpillars of vegetable brassicas

Caterpillars reduce yields of vegetable brassicas in many parts of the world. In some tropical areas effective control of the diamond back moth, *Plutella xylostella*, cannot be achieved due to high levels of resistance to chemical insecticides. In the UK vegetable brassicas may be damaged by the larvae of up to five species of lepidoptera each with different biologies. Of these five the most important economically are the small white, *Pieris rapae*, the cabbage moth, *Mamestra brassicae*, and *P. xylostella*. Their effective control requires a careful integration of pest monitoring, forecasting and the selection of appropriate products for control.

Like lettuce, vegetable brassicas are planted during many months of the year to provide continuity of supply of a range of vegetable types. Crops may be damaged by caterpillars at any stage in the development of the plant. Sophisticated methods of crop sampling to provide estimates of caterpillar populations with predetermined levels of accuracy are being developed which, when combined with trapping to monitor adult activity, are used to identify the need for spraying control intervention. Although pyrethroid insecticides are currently the preferred choice of growers for control, consumer and retailer demand for reduced use of chemical insecticides is driving the search for alternatives. *Bt* products are available, but they do not control *M. brassicae* effectively. The spectrum of pests killed by the transconjugate product of *Bt,* now marketed by Ciba Geigy as 'Agree', is greater than pure strains and provides opportunities in this market if commercial and registration issues can be overcome.

Codling moth on apples

Codling moth, *Cydia pomonella*, is a major pest of apples in many parts of the world. However, it is only one of a large complex of pests which without careful management can cause considerable reductions in the harvest of grade 1 fruit. In the past, widespread use of insecticides resulted in the development of secondary pests because their natural enemies were destroyed. As a consequence, sophisticated systems of integrated pest and disease management have been developed for use in apples orchards (Solomon, 1987, Anon., 1994), modifications of which are used in regions of intensive apple production throughout the world.

The effective control of codling moth is exacerbated by the cryptic habitat occupied by larvae immediately after egg hatch. Eggs are laid on leaves near fruit. After egg hatch, the neonate larvae burrow into fruit to feed and develop. As soon as the larva enters the fruit it is inaccessible to control. Accurate forecasts have been devised, based on a description of the interaction between larval development and temperature, which predict when key stages in the life cycle of the pest are available for control (Solomon & Morgan, 1996). The output of such models identifies the correct timing of control interventions as eggs hatch while pheromone trap samples indicate whether populations are sufficiently large to warrant control.

The wild type of the granulosis virus of *C. pomonella* (CpGV) was the first virus product to be registered for use on a food crop anywhere in the world. Experimental work has shown that CpGV is highly pathogenic to neonate larvae with only one to three capsules required to cause a lethal infection (Crook *et al.,* 1985). In addition, when CpGV is applied at the correct time in orchards, severe damage to fruit is reduced while the natural enemies of other pests are conserved (Glen & Payne, 1984). Neonate larvae did cause limited damage to the skin of apples prior to death.

Glasshouse tomato production

Long-season tomato production in north west Europe is highly competitive and driven by technology achieving yields in excess of 500 t per ha per annum. The key pests are the two-spotted spider mite, *Tetranychus urticae*, and the glasshouse whitefly, *Trialeurodes vaporariorum*. Following the development of resistance to insecticides, and more recently the widespread adoption of bumble bees for the pollination of crops, predators and parasitoids are now introduced routinely to control these pests. In such an environment control of other pests has to be compatible with these biological solutions and as a consequence sophisticated IPM systems have developed in protected tomato crops (Jacobson, pers. comm.).

Other pests that can cause considerable damage include the tomato moth, *Lacanobia oleracea*, and the tomato leafminer, *Liromyza bryoniae*. Larvae of *L. oleracea* may be controlled readily by applications of *Bt* as Dipel (Jarrett & Burges, 1982). *Liromyza bryoniae* larvae excavate mines in the mesophyll tissue of leaves where they may be controlled by the parasitoids *Diglyphus isaea* and *Dacnusa sibirica*. However, in early summer these biological control agents frequently fail to control leafminer populations and an alternative is required. Applications of the entomopathogenic nematode, *Steinernema feltiae*, as the commercial product Nemasys, have been found to be effective experimentally if the humidity remains sufficiently high for nematodes to find and infect their leafminer host (Williams & Macdonald, 1995). Such applications preserve the other biological components within the IPM system and enable fruit to be harvested without contravening the protocols set by retailers.

FUTURE OPPORTUNITIES

The opportunities for the future development of biopesticides lie in making them available for exploitation within any form of IPM system, be it ecological or technological. This will be achieved by focusing on both the regulatory procedures that control their use, and by the application of recent developments in biotechnology to remove some of the biological constraints that currently restrict their use.

The regulations applied to biopesticides throughout the world differ greatly between countries. Regulations are required to ensure the safety of the consumer, user and the environment. However, it is questionable whether these products, provided quality can be assured, need to be treated in the same way as chemical insecticides, particularly where wild-type micro-organisms are applied in the ecological regions from which they originate. It is vital that mechanisms are put in place that enables the use of such products to encourage a more ecological uptake of IPM which is vital for rural economies in resource-poor countries. Similarly, the regulatory requirements in more developed regions of the world, where IPM is frequently very technological, must operate on a geographical scale that will enable the commercial exploitation of biopesticides. The European Commission Directive 91/414/EEC "concerning the placement of plant protection products on the market" begins to provide a mechanism by which Europe, rather than individual member states, is the geographical region for which the registration could apply. These regulations have the potential to improve dramatically the commercial desirability of registering biopesticides, and hence their uptake in IPM systems.

Perhaps the most exciting opportunities are in overcoming the biological limitations in the use of biopesticides. Many laboratories are seeking to increase the persistence, speed of kill and the host range of pathogens. Persistence is being addressed primarily by formulation and will not be expanded here. Research to improve the speed with which biopesticides can kill their host is most advanced in the baculoviruses. The transformation of these viruses, either through gene deletion or gene addition, has become possible now that permissive insect cell lines have been developed. For example, strains of CpGV have been produced with the *egt* gene removed which has the effect of stopping host feeding. Gene addition has focused on the insertion of toxin genes from a diversity of sources; the search for new 'warheads' is under way in many laboratories.

The biological processes that determine host specificity are little understood. The host range of *Bt* can be increased by bringing together the toxins from different strains in novel combinations (Burges & Jarrett, 1988), and there may be similar opportunities for nematodes. In baculoviruses there are indications that host specificity may be under the control of a single gene. The ability to identify and manipulate such genes may make it possible to develop biopesticides that are effective against the spectrum of pests that are found on a single commodity e.g. the tortricid pests of apple, rather than a single host. The efficacy of many micro-organisms is limited in the environment inhabited by the host. Knowledge of micro-organism physiology, and hence the ability to manipulate it, can extend the usefulness of a product, particularly fungi that require high humidity (Hallsworth & Magan, 1995).

In conclusion, biopesticides do have considerable potential for use in IPM systems. This will be reached through a fuller understanding of the interaction between pathogens and their host at the population, whole organism and molecular levels and by the application of this knowledge in an appropriate regulatory framework.

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