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Factors in the success and failure of microbial insecticides in vegetable crops

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Abstract

A search for patterns in the success and failure of microbial insecticides in vegetable crops was conducted through review of four case studies: the use of *Bacillus thuringiensis* (*B.t.*) var. *tenebrionis* for control of the Colorado potato beetle, the use of *B.t.* var. *kurstaki* for control of the diamondback moth, the use of various *B.t.*s for control of lepidopterous pests in tomatoes and celery, and the use of a granulosis virus for control of potato tuber moth. With success defined in terms of achievement of technical goals (efficacy), commercial goals (end-user and insecticide manufacturer satisfaction) and social, or public goals (environmental and health safety), only certain of the case studies could be judged a success. These successes shared a variety of features including: (1) use of the microbial insecticide as a component, rather than as the sole agent, in an integrated crop management program; (2) unavailability of conventional insecticides, due to insecticide resistance, lack of registered products or mandatory IPM programs, provided incentive for the use of microbial insecticides; (3) modification of the expectation that microbial insecticides will perform within the chemical paradigm – fast, lethal and on contact; (4) exploitation of all possible benefits of the microbial insecticide, including safety to natural enemies, as well as efficacy against the target insect, and (5) support from large private and public institutions in the form of research, grower education, scouting programs, subsidized production, and economic and legal incentives to the use of microbial insecticides.

Introduction: defining success and failure

There is no single, robust definition of success (or failure) that meets the varying criteria of the many groups that have a stake in the use of microbial insecticides. The example of products based on *Bacillus thuringiensis* var. *tenebrionis* (*B.t.t.*) first marketed for control of the Colorado potato beetle (*Leptinotarsa decemlineata* [Say] Coleoptera:Chrysomelidae) in 1988, is a case in point. From the researcher's purely technical perspective, these products (which included Foil [Ecogen], M-One and M-Trak [Mycogen], and Novodor [Abbott],), when used properly, maintained insect populations consistently below the economic threshold level and controlled insects that were resistant to conventional insecticides; they were therefore judged to be a technical success (Zehnder & Gelernter 1989). Likewise, organic potato growers, who had in the past suffered from the lack of organic-approved Colorado potato beetle (CPB) products, welcomed these products with open arms. However, from the commercial perspective of the majority of (non-organic) potato growers, *B.t.t.* products were judged to be of marginal value, especially once more effective and easier-to-use products such as the chloronicotinyl insecticide, imidacloprid, was introduced to the marketplace. Furthermore, from the insecticide manufacturer's standpoint, *B.t.t.* products were never deemed a success, due to low consumer demand and low profitability; sale of *B.t.t.* based products was discontinued

Table 1. Microbial insecticides that satisfy technical (efficacy) goals, commercial goals (for end-users and microbial insecticide manufacturers) or the general public are indicated with a check (√) while those that do not are indicated with an 'X'

	Technical	End-user	Insecticide manufacturer	General public
B.t.t. for Colorado potato beetle	√	X	X	X
B.t.k. for diamondback moth (1980–1990)	√	√	√	X
B.t.k. for diamondback moth (1990–present)	X	X	X	X
B.t. in tomato IPM programs	√	√	√	√
GV for potato tuber moth	√	√	Uncertain	To be determined

by 1998 by almost all companies as a result. Finally, from the viewpoint of the general public, the benefits of these products have been negligible, since alternatives to the *B.t.t.* products such as imidacloprid are also relatively safe for humans and the environment.

In attempting to describe the potential for success or failure of microbial insecticides, we therefore face a problem. If we focus on the criteria for just one of the four groups described above, we are bound to develop a skewed vision of which microbes are most likely to succeed and which are most likely to fail. Yet if we require agreement among all of the concerned groups, our standards become unreasonably high, and we almost certainly condemn all microbial insecticides – and probably most insect control products, for that matter – to the dust heap as failures. This leaves us somewhere in between these extremes for a reasonable working definition of success. In this review, we will, somewhat arbitrarily, consider a microbial insecticide successful if it has met the criteria of at least two of the four groups described above: (1) the technical community; (2) end-users; (3) microbial insecticide manufacturers; and (4) the general public. In the example above, since the *B.t.t.* products only met the criteria of the technical community and of a minority of (primarily organic) growers, it would not be judged a success (Table 1).

Promoting success by limiting alternatives: *B. t.* var. *kurstaki* and the diamondback moth

As in the case of the Colorado potato beetle and *B.t.t.,* growers of cole crops first became interested in microbial insecticides only when they were desperate – when all other control options had failed due to widespread development of diamondback moth (*Plutella xylostella* [Linnaeus] Lepidoptera:Plutellidae) resistance to chemical insecticides. Beginning in the early 1980s, the use of products based on *B.t.* var. *kurstaki* (*B.t.k.*) such as Dipel (Abbott), Javelin (Novartis), MVP (Mycogen), and Condor (Ecogen) began to dramatically increase on cole crops. Unlike *B.t.t.*, however, efficacy of *B.t.k.* products was regarded by growers as good to excellent, and relatively easy to use. The extremely high toxicity of *B.t.k.* delta endotoxins for diamondback moth (DBM) larvae, almost 100 times that of the toxicity of *B.t.t.* for CPB larvae (Figure 1) is the primary reason for this difference in end-user experiences. As a result, there was a short, happy window of time where it indeed seemed as though microbial insecticides had finally found a market where they consistently performed as well as, or even better than, chemical insecticides. But the honeymoon was short-lived. By 1990, the use of up to 50 applications per year of *B.t.k.* products for control of diamondback moth larvae led to the

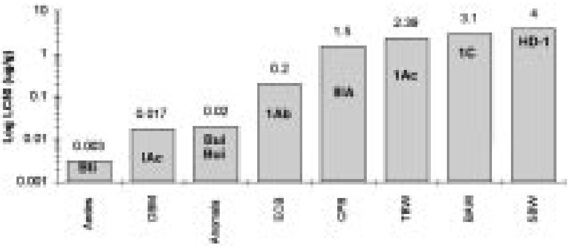

Figure 1. Potency, based on bioassay-generated LC_{50} values, of *Bacillus thuringiensis* delta endotoxins against larval insect species including the yellow fever mosquito (*Aedes*), the diamondback moth (DBM), the cupreous chafer (*Anomala*), the European corn borer (ECB: *Ostrinia nubilalis* [Hübner] Lepidoptera:Pyralidae), the Colorado potato beetle (CPB), the tobacco budworm (TBW: *Helicoverpa virescens* [Fabricius] Lepidoptera:Noctuidae), the beet armyworm (BAW) and the spruce budworm (SBW: *Choristoneura fumiferana* [Clemens] Lepidopetera:Tortricidae). Delta endotoxins assayed include protein mixtures isolated from *B.t.* var. *israelensis* (Bti), from *B.t.* var. *kurstaki* (strain HD-1) and from *B.t.* var. *japonensis,* strain BuiBui, as well as pure toxins such as CryIAc, CryIAb, CryIIIA. Potency values are averages of values found in the scientific literature from 1989–1995.

first case in history of field resistance to a *B.t.* product (Tabashnik *et al*. 1990). Field resistance to *B.t.k.* has since been confirmed in Hawaii, Florida, Japan (greenhouses only), the Philippines, Honduras, Costa Rica and Guatemala (Perez & Shelton 1997). To add insult to injury, we are now beginning to see the first incidence of diamondback moth resistance to *B.t.* var. *aizawai*, a strain which was successfully (though briefly) used to control DBM populations that were resistant to *B.t.k.* products (Liu *et al*. 1996).

In this example, we can therefore come to two very different conclusions about the success of microbial insecticides for DBM control, depending on the point in history that we choose to make our analysis. During the 1980s and early 1990s, the use of *B.t.k.* for control of DBM could have been judged as a success by almost any standards. The product was highly efficacious, end-users liked it, and private companies saw real growth in sales of *B.t.k.* products. However, by the mid-1990s, DBM resistance to *B.t.k.* in many key cole crop growing areas of the world made this product of minimal use to growers, and therefore to microbial insecticide manufacturers – a failure by almost any standard.

Comparison of the cases of *B.t.t.* for the CPB and *B.t.k.* for the DBM leaves the distressing message that you just cannot win. Either the products are not effective enough, leading to end-user dissatisfaction and private company withdrawal from the marketplace (as in the case of *B.t.t.*), or the products are so efficacious that they are overused, causing development of resistance (as in the case of *B.t.k.* and the DBM). Is it possible that this 'no-win' situation is the outcome of the unreasonable expectation that microbial insecticides can perform like chemical insecticides? Can our successes be longer-lived, more sustainable, if we change those expectations?

Promoting sustainable success: *B.t.* var. *kurstaki* in integrated tomato and celery programs

Avoiding the chemical paradigm

In most cases, the efficacy of microbial insecticides is inferior to the chemical insecticides that they might replace due to lack of acute toxicity, lack of residual activity, specificity, and lack of contact activity (in the case of *B.t.* and baculoviruses). By focusing exclusively on microbial insecticides as 'silver bullets' that will solve specific pest control problems, and by looking at only one pest at a time (as in the CPB and DBM examples above), are we overlooking some of the less tangible, longer-term benefits of the use of microbials? The widespread adoption of tomato and celery pest management programs that rely on *B.t.k.* products as much for their lack of disruption of natural enemy complexes, as for their ability to control lepidopterous pests, would suggest that this is the case.

Tomato IPM in Mexico, California and Ohio

Prior to 1986, lepidopterous pests on tomatoes (tomato pinworm, *Keiferia lycopersicella* [Walsingham] Lepidoptera:Gelechiidae*;* tomato fruitworm, *Helicoverpa zea* [Boddie] Lepidoptera:Noctuidae*;* beet armyworm, *Spodoptera exigua* [Hübner]*;* yellow striped armyworm (*Spodoptera ornithogalli* [Guenée] Lepidoptera:Noctuidae) were controlled with up to 40 applications per crop of chemical insecticides such as methomyl and permethrin. In addition to the expense and environmental problems caused by these applications, destruction of beneficial insect complexes resulted in upset infestations of leafminers (*Liriomyza* spp.) and whiteflies (*Bemisia* spp.), which in turn required additional insecticide applications for control (Bolkan & Reinert 1994).

To address these problems, an integrated program, which relies on various combinations of the components listed below, has been implemented in various forms on large hectarages of fresh and processing tomatoes in Mexico, California and Ohio (Bolkan & Reinert 1994, Trumble *et al*. 1994):

- pheromones for tomato pinworm mating disruption;
- *B.t.k.*, *B.t.* var. *aizawai* or abamectin (Avid, produced by Novartis) based products for fruitworm and armyworm control; release of the parasitoid wasp *Trichogramma pretiosum* for further fruitworm control;
- insecticidal soaps for whitefly control;
- development of economic thresholds for all pests;
- weekly scouting programs.

Because it was possible to see significant reductions, or the complete elimination of hard chemicals from tomato pest management programs, leafminer and whitefly populations were reduced via the resurgence of natural regulation by parasitoids and predators. In addition, replacement of methomyl sprays with *B.t.k.* applications for control of soybean loopers (*Pseudoplusia includens*) in nearby soybean fields also contributed to the build up of natural enemy complexes for control of whiteflies. Economic analyses indicate that growers on the IPM programs were usually more profitable ($64–$1000 per hectare) than growers using conventional insecticides, due to reduced frequency of pesticide applications and/or higher yields in the IPM fields. (Bolkan & Reinert 1994, Trumble *et al*. 1994).

Celery IPM in California

In celery, an IPM program targeted two key pests, the beet armyworm and *Liriomyza* leafminers, and produced similar results. The substitution of *B.t.* var. *aizawai* (Xentari, produced by Abbott Labs) for methomyl applications for control of beet armyworm larvae allowed natural enemies of leafminers to survive, resulting in a reduced need for insecticide applications targeted against leafminers. When necessary, applications of abamectin (Avid, produced by Novartis), which has minimal activity against parasitoids and predators, were made against leafminers. As for tomatoes, the celery IPM program has demonstrated increased profitability (up to $410 per hectare in grower validation trials) when compared to the higher input standard chemical program (Trumble *et al*. 1997).

Sustaining success

These two IPM programs satisfy all of the major criteria for success described above. Technical goals are satisfied in the high level of demonstrated efficacy, end-users are more than satisfied with increased profitability, microbial insecticide manufacturer's sales are gradually increasing, and even the public profits, through decreased pesticide residues, particularly on processed foods (the issue of toxic residues on processed foods has received increased regulatory and media attention in the past few years). Best of all, these programs continue to be adopted on increasing hectarages and, due to the integrated nature of the program, are less likely to be threatened by development of resistance to microbial insecticides, or by introduction of new lepidopteran active products.

Which factors have contributed to this more sustainable success? Certainly, by successfully utilizing the multiple benefits of microbial insecticides – efficacy, as well as safety for beneficial insects – the futile comparison with rapid knock-down, lethal chemical insecticides can be put where it rightfully belongs: in the trash bin. It is interesting to note that the toxicity of *B.t.* delta endotoxins to tomato and celery pests is similar to that of *B.t.t.* for CPB (Figure 1). In other words, on the basis of efficacy alone, *B.t.* products might not succeed in these systems. However, in combination with their ability to preserve natural enemies, *B.t.* products begin to have an edge over chemical insecticides. Due to the lack of strong natural enemy complexes on potatoes and cole crops, this benefit of *B.t.* could not be as fully exploited in these case studies.

The tomato and celery IPM programs also differ from the CPB and DBM experiences in their lack of reliance on a single product to control all key pests, thus decreasing the risk of the kind of resistance we saw develop in DBM populations exposed to incessant applications of *B.t.* The likelihood that a new, effective chemical insecticide can completely displace *B.t.* in these programs, as in the example of imidacloprid in potatoes, is also less likely (though not impossible), primarily because of strong grower education programs, scouting programs and even mandatory requirements for IPM implementation that have been promoted by the University of California and by large food processors such as the Campbell Soup Company. Of particular interest is the goal, successfully accomplished by Campbell's by 1994, to reduce chemical pesticide applications by 50% on all crops grown for the company. Growers under contract with Campbell's cooperate in IPM demonstrations in their own fields, with the understanding that two consecutive years of success with the IPM program obligates them to adopt the IPM program on their entire hectarage (Bolkan & Reinert 1994).

The role of large institutions, be they public or private, in promoting and even mandating the use of microbial insecticides and IPM programs has always been of importance in forestry and vector microbial control programs – situations where the public, or 'collective good' (Weisbrod 1978) was more clearly at stake. A review of IPM programs in tomatoes and celery reveals that these institutions may also be of importance in insuring the success of microbial insecticides in vegetable and other commodity crops. This is despite the traditional view that market forces (in the form of growers, striving for short-term profitability), rather than the public good, are the driving forces behind pest control decisions in these high value markets. Giving this viewpoint an odd twist, we see that in the tomato and celery IPM programs, it is private, for-profit institutions such as Campbell's, whose self-interested goals (public image, stock-holder satisfaction, reduced pesticide residues in processed foods), have led them to embrace and mandate the use of microbial insecticides and IPM more actively than individual vegetable growers. The role of large institutions in the success of microbial insecticides is further explored in the example of the granulosis virus for potato tuber moth, below.

Moving towards the future: granulosis virus for potato tuber moth control

This review began with a discussion of a failed *B.t.* product on potatoes, and will wrap up with a description of a granulosis virus on potatoes that has the potential to be quite successful, based in part on incorporation of many of the lessons learned above.

The potato tuber moth, *Phthorimaea operculella* (Zeller) Lepidoptera:Gelechiidae, is the most damaging pest of potatoes in the tropical and Mediterranean climates of India, the Philippines, Thailand, North Africa, Peru and the Middle East. Damage occurs primarily in storage, when newly hatched larvae bore into tubers. When infestations are high, the entire store of potatoes, frequently a staple for poor, rural farmers can be destroyed. And since potatoes are stored near, or in the home in many areas of the world, reduced use of toxic insecticides is a goal of both farmers and government agencies (Lagnaoui *et al*. 1996, Winters & Fano 1997).

Beginning in the 1980s, International Potato Center (CIP) research on IPM strategies for the potato tuber moth (PTM) was initiated, resulting in development of a comprehensive program that is now being implemented in Peru, Egypt, Tunisia, Morocco, Turkey and Yemen (Lagnaoui *et al*. 1996). Components of this program include the following cultural and pest control components:

- hilling and/or regular irrigation to prevent adult PTM from laying eggs on mature tubers that are exposed via cracks in drying soil;
- early planting and harvest to reduce late season PTM egg deposition on mature tubers;
- sanitation of storage facilities and disposal of infested tubers prior to storage;
- use of indigenous, insect-repellent materials, such as eucalyptus, in storage areas to act as a physical barrier and aromatic repellent to PTM;
- pheromone traps and field scouting to monitor PTM populations and allow optimal timing of insecticide applications;
- use of *Baculovirus phthorimaea* (granulosis virus of PTM) to control larval PTM populations in the field and in storage.

When some or all of these practices were combined in large-scale grower trials and test market programs on several thousand tons of stored potatoes, PTM infestations were significantly reduced, generally to less than 5%, and with high grower satisfaction (Winters & Fano 1997). Mass production facilities, based on a cottage-type industry model, have been built (with CIP, non-governmental organization and government support) in Peru, Egypt and Tunisia, with optimization of virus production, quality control and profitability of an ongoing process.

Many of the positive features of the tomato and celery IPM programs described above are reflected in the PTM program as well, including the use of an integrated program (rather than a single product/single pest program), and development of strong research, development, scouting and education programs to support IPM implementation. For this reason, the use of microbial insecticides for PTM control has so far met technical and end-user success criteria. However, due to its pre-commercial stage of development, it is too early to tell whether the criteria of manufacturing companies and the public will also be fulfilled.

Addressing the ‘public good’

Can we use the criteria developed in this review to help predict the success of the PTM program? From the standpoint of private companies, the success of this project is problematic. Although there is some evidence that the virus can be produced economically (Winters & Fano 1997), the market is small and limited to only one insect pest. And with poor rural farmers as the major consumers, the value of this market is not high. For these reasons, private companies may have little incentive to explore the PTM virus as a commercial product. Yet there are real and compelling reasons why this program is important, despite its lack of commercial appeal. First, it is targeted to support poor rural potato farmers, in their efforts to increase yields while decreasing their exposure to toxic pesticides. Secondly, as with all microbial insecticides, the use of the PTM virus will result in environmental and health benefits that will be enjoyed by the public at large. Who is responsible for addressing these needs if private industry does not?

In the case of tomato and celery IPM programs, the health and environmental benefits that the public reaped were generated almost inadvertently, through the collaboration of end-users, public universities and private food processors. However, when public good benefits such as these are not addressed by private companies, it is frequently the role of the public sector to address these ‘market failures’ (Weisbrod 1978). In the case of the PTM, sustained success of the virus and IPM programs may therefore very well continue to depend on financial support from public institutions such as national governments and public universities, the CIP and non-governmental organizations, such as CARE.

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