Chapter 2

Plutella xylostella (Linnaeus, 1758) (Lepidoptera: Plutellidae): Tactics for Integrated Pest Management in Brassicaceae

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1. Introduction

The diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), is one of the most serious pests of cultivated Brassicaceae worldwide [1,2]. This crucifer specialist may have its origin in Europe [3], South Africa [4], or East Asia [5], but is now present worldwide wherever its host plants exist [6].

In the first instar, the larvae enter into the leaf parenchyma and feed between the upper and lower surfaces of leaves creating mines. In the second instar, the larvae leave the mines, and from the second to the third instar, they feed on the leaves, destroying the leaf tissue except for the upper epidermis, leaving transparent “windows” in the leaves. Fourth-instar larvae feed on both sides of the leaves [7]. This insect has a short life cycle, around 18 days, and its population may increase up to 60-fold from one generation to the next [8]. Studies indicate that the moths can remain in continuous flight for several days while covering distances up to 1000 km per day, but how the moths survive at such low temperatures and high altitude is not known [1]. In eastern Canada, annual populations of diamondback moths originate from adult migrants from the United States [9].

P. xylostella was the first crop insect reported to be resistant to dichloro-diphenyl-trichloroethane (DDT), only 3 years after the start of its use [10], and subsequently it has shown significant resistance to almost every insecticide applied in the field, including new chemical compounds [11,12]. In addition, diamondback moth has the distinction of being the first insects to develop resistance in the field to the bacterial insecticide *Bacillus thuringiensis* [13,14]. The resistance of *P. xylostella* populations to *B. thuringiensis* has been observed by [15-23] in

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the USA (Florida, Hawaii, and New York), Central America (Mexico, Costa Rica, Guatemala, Honduras, and Nicaragua), and Asia (Japan, China, Malaysia, and the Philippines). In Brazil, [24] it was documented this pest's resistance in environments where *B. thuringiensis* is commonly used as a bioinsecticide.

This has prompted increased efforts worldwide to develop IPM programs for *P. xylostella*, based principally on new management tactics that are not yet used in the field for this pest [8,25,26]. In this chapter, we give an overview of the association of *P. xylostella* with its host plants and natural enemies, and describe management strategies and practices for control of the diamondback moth.

2. Tactics for integrated pest management

2.1. Biological control

Biological control can be defined as the use of one type of organism to reduce the population density of another. Biological control has been used for approximately two millennia, and has been widely used in pest management since the end of the nineteenth century [27]. The following types of biological control can be distinguished: natural, conservative, inoculative (or classical), and augmentative. Natural biological control involves the reduction of pest organisms by their natural enemies and has been occurring since the evolution of the first terrestrial ecosystems, 500 million of years ago [28]. It takes place in all of the world's ecosystems without any human intervention, and, in economic terms, is the greatest contribution of biological control to agriculture [29]. Conservation biological control consists of human actions that protect and stimulate the performance of naturally occurring enemies [30]. In inoculative biological control, natural enemies are collected in an exploration area (usually the area of origin of the pest) and then released in new areas where the pest was accidentally introduced. In augmentative biological natural control, natural enemies are mass-reared in biofactories for release in large numbers to obtain immediate pest control [28].

2.1.1. Entomophagous agents: parasitoids and predators

Parasitoids can be defined as insects that are only parasitic in their immature stages, kill their host in the process of development, and have free-living adults that do not move their hosts to nests or hideouts [31].

All stages of the diamondback moth are attacked by numerous parasitoids and predators, with parasitoids being the more widely studied. Over 90 parasitoid species attack the diamondback moth [32]. Egg parasitoids belonging to the polyphagous genera *Trichogramma* and *Trichogrammatoidea* contribute little to natural control and require frequent mass releases. Larval parasitoids are the most predominant and effective. Many of the effective larval parasitoids belong to two major genera, *Diadegma* and *Cotesia*; a few *Diadromus* spp., most of which are pupal parasitoids, also exercise significant control [1]. The majority of these species come from Europe where the diamondback moth is believed to have originated [1]. In countries near Brazil, such as Argentina, *P. xylostella* larval parasitoids collected in the field include the species *Diadegma insulare* (Cresson) (Hymenoptera: Ichneumonidae), *Oomyzus sokolowskii* (Kurdjumov) (Hymenoptera: Eulophidae), and *C. plutellae* (Kurdjumov) (Hymenoptera: Braconidae) [33].

Seven species of parasitoids were observed in a *P. xylostella* population on cabbage crops in the Brasilia region of Brazil, with the two most common species being *Diadegma liontiniae* (Brethes) (Hymenoptera: Ichneumonidae) and *Apanteles piceotrichosus* (Blanchard) (Hymenoptera: Braconidae). *Cotesia plutellae* (Kurdjumov) (Hymenoptera: Braconidae) and *Actia* sp., previously more abundant, had become very minor parasitoids. Six species of hyperparasitoids emerged from *D. liontiniae* and *A. piceotrichosus*, showing a high diversity of natural enemies in this region of recent colonization by *P. xylostella* [34].

In organically farmed kale in Pernambuco, Brazil, seven natural enemies of *P. xylostella* were observed: three parasitoids, *C. plutellae* Kurdjumov (Hymenoptera: Braconidae), *Conura pseudofulvovariegata* (Becker) (Hymenoptera: Chalcididae) and *Tetrastichus howardi* (Olliff) (Hymenoptera: Eulophidae), and four predators, *Cheiracanthium inclusum* (Hentz) (Araneae: Miturgidae), *Pheidole* sp. Westwood (Hymenoptera: Formicidae), and nymphs and adults of *Podisus nigrispinus* (Dallas) (Hemiptera: Pentatomidae) [35].

Several studies have been conducted in Brazil to examine whether these entomophagous agents of the diamondback moth could be used as a biological control for this pest in crucifer crops.

Parasitoids of the genus *Trichogramma* are among the entomophagous agents that have already been studied for *P. xylostella*. The species *T. pretiosum* Riley (Hymenoptera: Trichogrammatidae), Tp8 strain, can parasitize approximately 15 *P. xylostella* eggs in the first or second generation when reared in this host under laboratory conditions, with 100% emergence, and 10 to 11 days for adult emergence [36]. Eggs of two *P. xylostella* populations, one reared on kale leaves and the other on broccoli leaves, were exposed to the *T. pretiosum* Tp8 strain, and the number of parasitized eggs was 5.8–9.4 on kale and 3.2–8.4 on broccoli [37]. Furthermore, the optimal way to mass rear this parasitoid in the laboratory is to use eggs glued to blue, green, or white colored cards [37].

The impact on non-target species, particularly *Trichogramma*, of insecticides for *P. xylostella* control should be analyzed because some are toxic to these parasitoids in crucifers. Endosulfan and etofenprox, classified as class-4 toxic products, are extremely toxic to the parasitoids. Triflumuron, classified as a non-toxic product, is selective for these parasitoids in the eggs of *P. xylostella* [26]. The combination of chemicals or natural insecticidal products from vegetables with certain cultivars of crucifers enables more effective management of the diamondback moth, particularly in the case of the interaction between pyroligneous extract and cabbage. However, the interaction among cultivars and products can be detrimental to the effectiveness of *T. pretiosum* and *T. exiguum*, and thus requires a careful evaluation to minimize the impact on these natural enemies [38]. Bioinsecticides based on *B. thuringiensis* for controlling *P. xylostella* can influence the parasitoid *T. pretiosum* in the moth's eggs. The application of isolates of *B. thuringiensis* on *P. xylostella* larvae influenced the parasitism of *T. pretiosum* in eggs of subsequent pest generations [39].

Another parasitoid of *P. xylostella* larvae, which has been studied in Brazil, is *O. sokolowskii*. The duration of the immature stage of these parasitoids can range from 12.9 to 31.6 days at 28 and 18°C, respectively, and the number of adults emerged per pupa of *P. xylostella* varies between 7.3 and 12, with a sex ratio of between 0.86 and 0.91 [40]. During a year, the number of generations of *O. sokolowskii* is always higher than that of *P. xylostella*, suggesting that *O. sokolowskii* could develop up to 24 generations per year while the diamondback moth could reach 20 annual generations [40]. Furthermore, the *O. sokolowskii* parasitoid is able to disperse and parasitize *P. xylostella* throughout a kale field up to 24 meters from the release point [41].

Another larval parasitoid studied in Brazil for *P. xylostella* is *A. piceotrichosus*, which was collected in the Rio Grande do Sul State. Its immature stage was observed to last 14.6 to 15.5 days and its adult longevity was found to be 12.7 to 13.4 days [42].

Among the stink bug predators, *P. nigrispinus* has great potential for use in *P. xylostella* control. *P. nigrispinus* has been reported preying on *P. xylostella* in crucifer crops [35], and, furthermore, this predator consumed on average 10.9 larvae or 5.5 pupae in 24 h [43]. Adults of *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) has been reported consuming 5.9 diamondback moth eggs in 24 h [44].

2.1.2. Entomopathogens: Bacteria

The occurrence of *P. xylostella* populations of resistant to certain active ingredients, like synthetic and biological insecticides, has caused a considerable increase in research directed at developing tactics for Integrated Pest Control based on economic, social, and ecological parameters [21,45-47).

Recent studies on control strategies and population reduction of *P. xylostella* using microorganisms has been increasingly cited in the scientific community, with emphasis on the entomopathogenic bacterium *B. thuringiensis* Berliner (1911) [48-51,39].

This entomopathogen can be easily found in different environments [52,53], and it is characterized by a variety of strains, each forming one or more protein crystals (Cry) and cytolytic toxins [54] that have insecticidal activity and determined its efficiency as a control on certain agricultural pests. Another type of insecticidal protein that can be synthesized by some strains of *B. thuringiensis* is “Vegetative Insecticidal Proteins” (Vip), whose insecticide action spectrum operates in different insect species [55].

A long history of intensive research has established that their toxic effect is due primarily to their ability to form pores in the plasma membrane of the midgut epithelial cells of susceptible insects [56,57]. The presently available information still supports the notion that *B. thuringiensis* Cry toxins act by forming pores, but most events leading to their formation, following binding of the activated toxins to their receptors, remain relatively poorly understood [58].

Strains of *B. thuringiensis* can produce from one to five toxins that represent a large variability in toxicity and interfere in the expression levels and the spectrum control of insects, and differ in their specificity to certain species [59]. For example, the Cry proteins are show high toxicity to insects of the orders Lepidoptera, Coleoptera, Hymenoptera, Diptera, Orthoptera, and Mallophaga, and to other organisms such as nematodes and mites [60,54,61].

Among the different protein crystals identified in insect control, 59 toxins were tested against 71 Lepidoptera species [62]. The broadest range of toxins was tested against *P. xylostella* (43 toxin types), which was one of only 12 species that were tested against 15 toxins or more [62].

In Brazil, *P. xylostella* is controlled using entomopathogenic bacteria in phytosanitary applications of formulation products properly registered for a particular crop, most commonly biological products containing *B. thuringiensis* var. *kurstaki*, which expresses Cry1Aa, Cry1Ab, and Cry1Ac toxins [49] (Table 1).

Crops	Commercial Products	Chemical Groups	Active Ingredients	Formulation	Class	
					Toxicological	Environmental
Broccoli	Bac Control	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
	Dipel	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	II	IV
	Thuricide	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
Cauliflower	Bac Control	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
	Dipel	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	II	IV
	Thuricide	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
Cabbage	Able	Biological	*B. thuringiensis* subsp. *kurstaki*	SC	III	IV
	Agree	Biological	*B. thuringiensis* subsp. *aizawai* GC 91 + *B. thuringiensis* subsp. *kurstaki*	WP	III	IV
	Bac Control	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
	Dipel	Biological	*B. thuringiensis* subsp. *kurstaki*	WG	II	IV
	Dipel	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	II	IV
	Thuricide	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
	Xentari	Biological	*B. thuringiensis* subsp. a*izawai*	WG	II	III
Kale	Bac Control	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV
	Dipel	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	II	IV
	Thuricide	Biological	*B. thuringiensis* subsp. *kurstaki*	WP	IV	IV

Source: [63]. WP = Wettable Powder; WG = Water-Dispersible Granules; SC = Suspension concentrate.

Table 1. Commercial products based on *Bacillus thuringiensis* recommended for controlling the population of *Plutella xylostella* in different brassica crops.

However, the low variability in the number of toxins related to formulated biological products, combined with a high number of applications in the field, puts selection pressure on the population of *P. xylostella* and, consequently, expression of resistance of this pest to protein crystals has been observed since the 1990s [20,24].

The development of resistance in *P. xylostella* populations is related to the binding of these toxins with the intestinal epithelium, which occurs through the same membrane receptors [19,22].

Some alternative methods of resistance management of this pest towards *B. thuringiensis* toxins can reduce resistance and even make it possible to break the resistance to biological products [22,64].

According to [49], mixed formulations of different bacteria or isolates of *B. thuringiensis* that have a wide variety of *Cry* toxins, organized in isolation or together, have the ability to reduce selection pressure and, consequently, the development of new cases of resistance in populations of *P. xylostella*.

To improve the biological control of *P. xylostella* using this entomopathogenic bacterium, several studies have initially focused to on the characterization of new strains of *B. thuringiensis*, with the objective of discovering more efficient insecticides and implementing them in new formulations [65,66,51]. In a study conducted by [49] using stored grains and different strains of *B. thuringiensis* from soils of several regions of Brazil, there was high mortality (98–100%) of second-instar larvae of *P. xylostella*. These results have demonstrated that a high variability of *Cry* genes in the same strain can constitute a substantial tool for resistance management of this pest, with subsequent use in the synthesis of new biological products.

In pathogenicity tests, the strains behave in different ways, and few of them are able to cause total mortality in the insects analyzed. In research conducted by [51], approximately 19% of the strains tested caused total mortality to second-instar larvae of *P. xylostella* between 24 and 48 hours.

In this case, in addition to pathogenicity and virulence tests, researchers should analyze the sublethal effects of these strains on the remaining individuals, an important parameter in the toxicological evaluation of *B. thuringiensis* strains [67,68].

Many biological characteristics of *P. xylostella* may be influenced by the sublethal effects of these toxins, causing discernible changes in insect behavior, such as appetite loss, decreased movement with subsequent paralysis, change in the tegument color from bright green to dark yellow or dark brown, and loss of reaction to touch [69,51].

According to [51] and [8], the most pronounced biological changes observed between phytosanitary applications with strains and commercial products based on *B. thuringiensis* were in the viability of larvae and pupae and the weight of pupae. The biological characteristics less influenced by these strains were related to the caterpillar and pupal period and sex ratio [8].

The behavior of strains or commercial products based on *B. thuringiensis* that result in individuals surviving phytosanitary application, but that provide sublethal effects in subsequent generations, may be a significant tool for Integrated Pest Management [8], the objective of which is to improve management of the pest through interactions with other control methods, such as biological control with predators and parasitoids, which will reduce the population density due to sublethal effects caused by strains of *B. thuringiensis*. The remaining pests may be a food source and host for other insects considered beneficial to agriculture, and can help maintain and assist the populations of these arthropods in different crops.

The Integrated Management of *P. xylostella* based on biological control with the entomopathogenic bacterium *B. thuringiensis* is an important method for reducing the population density of this pest in brassica crops. However, the use of this control must be well planned, because there are populations of this pest resistant to biological products, necessitating the use of certain methods of resistance management to eliminate these harmful individuals and, perhaps, prevent future problems with the development of resistant populations that can undermine the whole program of rational control of this pest.

2.1.3. Entomopathogens: Fungi

There is no fungus-based bioinsecticide registered for crucifer crops in Brazil; however, some entomopathogenic fungi have been studied to determine their potential as a biological control agent for *P. xylostella*. Among the fungi that have been studied for their activity against *P. xylostella*, *Paecilomyces tenuipes* caused the highest mortality to third-instar *P. xylostella* larvae, with an LC_{50} of 1.09×10^6 spores/mL at 25°C [70].

The most active crude protein extract, isolated from the CNZH strain of *Isaria fumosorosea*, produced 83.3% mortality in third-instar larvae 6 days post treatment [71]. Furthermore, it has been found that a synergism exists between the fungus *I. fumosorosea* and a plant secondary chemical, and that larval deaths were directly related to the concentration of each component in the mixtures and their cumulative effect was evident for an extended period [72].

In addition to the species already mentioned, the fungi *Metarhizium anisopliae* and *Beauveria bassiana* were also studied for the control of *P. xylostella*. Several strains from Benin were tested and found to cause 94% larval mortality [73]. Strains obtained in Brazil have also been tested and caused mortality to *P. xylostella* larvae ranging from 70% to 96% [74].

2.1.4. Entomopathogens: Nematodes

Research on the control of Lepidoptera with entomopathogenic nematodes has focused on the diamondback moth [75]. Field studies on cabbage in Java (Indonesia) confirmed that *Steinernema carpocapsae* can be used as a substitute for ineffective chemical insecticides [76]. Diamondback moth eggs are deposited and the emerging larvae feed on the underside of the leaves. The control of young caterpillars with entomopathogenic nematodes can therefore be optimized by directing the nematode spray to the lower side of the leaves [75]. The use of a surfactant for lowering the surface tension and of a polymer for increasing the viscosity significantly improved nematode performance against *P. xylostella* [77]. The performance of these adjuvants is, however, influenced by the spray application technique [75].

2.2. Chemical control

The chemical control method, recommended as one of the tools or tactics of Integrated Pest Management, is still the main strategy for reducing pest populations among crucifer producers. This preference is due to the practicality, speed, and efficiency of controlling insects considered agricultural pests, particularly *P. xylostella* [78].

The chemical groups used to control this pest have great variability in terms of the active ingredient, formulation, and toxicological and environmental classes (Table 2).

Crops	Chemical Group	Active Ingredient	Formulation	Class	
				Toxicological	Environmental
Broccoli	Pyrethroid	Deltamethrin	EC	III	I
	Oxime Methylcarbamate	Methomyl	SL	I	II
	Organophosphate	Acephate	SP	II	III
Canola	Pyrethroid	Bifenthrin	EC	II	II
Cauliflower	Pyrethroid	Deltamethrin	EC	III	I
	Pyrethroid	Permethrin	EC	III	II
	Organophosphate	Acephate	SP	II	III
	Naphthyl Methylcarbamate	Carbaryl	WP	III	II
Cabbage	Anthranilamide+Pyrethroid	Clorantraniliprole+Lambda-cyhalothrin	SC	II	I
	Tetranortriterpenoid	Azadirachtin	EC	III	IV
	Benzoylurea	Teflubenzuron	SC	IV	II
	Benzoylurea	Lufenuron	EC	IV	II
	Benzoylurea	Novalurom	EC	III	II
	Pyrethroid	Deltamethrin	EC	III	I
	Pyrethroid	Permethrin	EC	I	II
	Benzofuranil Methylcarbamate	Carbofuran	GR	III	II
	Oxime Methylcarbamate	Methomyl	SL	I	II
	Organophosphate	Acephate	SP	II	III
	Analog of Pyrazol	Chlorfenapyr	SC	III	II
	Phenilthiourea	Diafenthiuron	WP	I	II
	Anthranilamide	Chlorantraniliprole	SC	III	II
	Oxadiazine	Indoxacarb	WG	I	III
	Naphthyl Methylcarbamate	Carbaryl	WP	III	II
	Spinosyns	Spinosad	SC	IV	III
Kale	Pyrethroid	Deltamethrin	EC	III	I
	Oxime Methylcarbamate	Methomyl	SL	I	II
	Organophosphate	Acephate	SP	II	III
	Pyrethroid	Permethrin	EC	III	II

Source: [63]. EC = Emulsion Concentrate; SL = Soluble Concentrate; SP = Soluble Powder; WP = Wettable Powder; SC = Suspension concentrate; GR = Granules; WG = Water-Dispersible Granules.

Table 2. Chemical groups and active ingredients registered for *Plutella xylostella* control in different brassica crops.

Among the pesticides recommended for different brassicas, the chemical group of pyrethroids represents one of the most important for *P. xylostella* control. Chemical control of *P. xylostella* using a synthetic pyrethroid is recommended when larval density exceeds an economic threshold, which varies in relation to the growth stage of the crop and environmental conditions [79,80]. However, the inappropriate use of these chemical products has considerably increased the frequency of resistance in different diamondback moth populations to some types of active ingredients of this chemical group [81,82,24,83]. According to [84] and [82], *P. xylostella* populations are considered very prone to developing resistance to some active ingredients. In addition to lowering the pesticide efficiency, increasing the frequency of application may not lead to a significant reduction in crop damage.

This may be due to the biological characteristics of this species, the life cycle of which is short when compared to that of other insects, and to the cultural practice of constantly applying pesticides with the same active ingredients in more concentrated doses, without providing a chemical molecule rotation or an appropriate dosage as listed on the label of the phytosanitary product used [24].

In the context of Integrated Pest Management, cultural, physical, plant resistance, biological, and chemical control methods may be important strategies in the success of the *P. xylostella* control program [85]. Techniques such as crop residue removal, management of the interval between crops, use of tolerant cultivars, use of sprinkler irrigation, application of plant and biological products and reduction in the number of pesticide applications by measuring the economic injury level, used harmoniously and consciously, can provide significant improvement in the quality of products and the system in which the culture is embedded [86-90,83].

After a rational application of chemical controls, the first response observed in the field is the high larval mortality of *P. xylostella* in direct proportion to the commercial product concentration recommended for the determined culture [91,83]. Another response to phytosanitary application is a significant alteration in the life cycle of the insect, principally the larval period, because many chemical compounds present in insecticides affect the process of ecdysis, interfering with the transition between instars, and thereby act as a growth regulator [83].

Among the types of insecticides recommended for the control of *P. xylostella*, growth regulators have been found to have low interference with the activity of predators, parasitoids, and entomopathogenic fungi, because they do not affect the embryogenesis and reproduction of this pest, which is important since the parasitoid larvae live inside the pest's eggs before emerging as adults [85,90,38]. This is important principally because the physiological selectivity of this chemical group makes them more toxic to the pest than to the biological control agent [92,93,38,94,26].

Insecticides of plant origin are also a very important group for the population management of this pest. Among these, neem extract (*Azadirarachta indica*) has shown significant results in the control of *P. xylostella*, affecting the growth, larval mortality during ecdysis, oviposition, deformation in pupae and adults, and the physiological processes of reproduction, such as inadequate egg maturation and infertility, that interfere with larval hatching [95,90,83,38,96].

In this context, managing the population of *P. xylostella* using chemical control methods can be a very interesting strategy if well used, because of the large number of chemical groups with different active ingredients, which enables a chemical molecule rotation and prevents the development of resistance. These products can be used with other control techniques to reduce the number of applications of pesticide and improve the quality of the final product. Another very important consideration in choosing the chemical product is its selectivity, because many chemicals have high selectivity for the host but not for biological control agents, which contributes to the maintenance of populations considered beneficial to the integrated management of *P. xylostella*.

2.3. Plant resistance

The crop forms a template for various interactions between pests and their environment, and varietal resistance to pests is a key component for stabilizing an IPM system [97].

Plants have a bewildering array of responses to herbivory, broadly categorized as direct and indirect defenses and tolerance [98]. Some primary wax components, including specific long-chain alkyl components, have allelochemical activity that influences the host acceptance behavior of *P. xylostella* larvae [99]. Furthermore, glucosinolates, a category of secondary products, are found primarily in species of the Brassicaceae. When tissue is damaged, for example by herbivory, glucosinolates are degraded in a reaction catalyzed by thioglucosidases, called myrosinases, which are also present in these species. This causes the release of toxic compounds such as nitriles, isothiocyanates, epithionitriles and thiocyanates. The glucosinolate-myrosinase system is generally believed to be part of the plant's defense against insects, and possibly also against pathogens [100].

Among various cultivars of crucifers observed, the cabbage 'chato de quintal' showed a high level of the substance glucobrassicin, and was classified as moderately resistant to *P. xylostella* [101].

Several studies have been conducted in Brazil to determine the crucifer cultivars resistant to *P. xylostella* for use in the management of this pest. Among the crucifers that are marketed in Brazil—cabbage cultivars, broccoli, kale, and cauliflower—cabbage cultivars were more resistant, and kale cultivars were more susceptible to diamondback moth [8]. When compared only cultivars of kale, it was found that 'Ribeirão Pires I-2620' was the most susceptible to two generations of diamondback moth [102].

The use of silicon in the integrated management of diamondback moths may help to reduce the use of pesticides. Silicon damages the jaws of larvae, limiting ingestion and causing high mortality [103].

2.4. Cultural control

The current pest management tactics pursued by growers focus on the protection of crucifer seedlings, using both cultural and chemical means, in some seasons in the established crops [104]. Because of the failure of insecticides to control the diamondback moth, interest is growing in the use of cultural controls in commercial crucifer production. Some of the classical control measures that have been tried with some success are intercropping, use of sprinkler irrigation, trap cropping, crop cover rotation, and clean cultivation [1].

The mortality of *P. xylostella* was significantly higher with the intercropping of Chinese cabbage (*Brassica chinensis*) with garlic (*Allium sativum*) and lettuce (*Lactuca sativa*) than in monocultures of Chinese cabbage. These results suggest that intercropping can suppress the diamondback moth populations for a long period rather than just the short term [105]. Furthermore, studies conducted in Brazil of the intercropping of cabbages with other crop plants (cabbage and green onion, cabbage and cilantro, and cabbage, green onion, and cilantro) did not reduce the rate of parasitism of *P. xylostella* larvae by *O. sokolowskii*, which makes it promising for diamondback moth biological control; however it did not interfere with cabbage colonization by the diamondback moth [41].

A study investigating the impact of irrigation systems on diamondback moth infestation in cabbage noted that when irrigation water was applied by sprinkler-irrigation, diamondback moth infestations were reduced by 37.5–63.9% compared with a drip-irrigated control [106].

Glucosinolates are biologically active natural products characteristic of crucifers, and crucifer-specialist insect herbivores, such as *P. xylostella*, frequently use glucosinolates as oviposition stimuli. Benzylglucosinolate-producing tobacco plants were more attractive for oviposition by female *P. xylostella* than wild-type tobacco plants. As newly hatched *P. xylostella* larvae were unable to survive on tobacco, these results represent a proof-of-concept strategy for rendering non-host plants attractive for oviposition by specialist herbivores with the long-term goal of generating efficient dead-end trap crops for agriculturally important pests [107].

With regard to crop cover for crucifers, a broccoli cover-cropping system (cereal rye) resulted in fewer leaves, smaller plants, and a slightly reduced yield when compared to the other systems. Strip-cropping broccoli with potatoes did not convey any agronomic advantages. Gross margin analysis revealed that on a total system basis, a 2.2% yield improvement or a 7% price premium was required to make the cover crop system perform as well as conventional practice [108].

Another study looked at the effect of two diversification strategies, one a broccoli/potato (*Solanum tuberosum*) strip crop comprising 1.65-m (tractor width) replications of two rows of potatoes and two rows of broccoli, and the other a cereal rye (*Secale cereale*) cover crop, which formed a sacrificial planting that was killed and rolled flat to minimize weed competition and improve the agronomic performance of the subsequent broccoli crop. In this case, it was observed that *P. xylostella* eggs, and the subsequent larvae and pupae, were less abundant on broccoli with the cover crop, probably due to interference with host location and oviposition processes. The strip crop had no effect on broccoli crop yield [109].

2.5. Sex pheromones

The potential for using synthetic sex pheromone traps as a simple and practical method of monitoring population densities of insect pests has been investigated in many crop systems. Sex pheromones of *P. xylostella* have already been synthesized for use in the management of this pest in crucifers [110]. Thus, trap catches can be used to forecast infestations during periods that coincide with high *P. xylostella* infestations [111].

Currently, pheromone-baited traps in the Prairie Pest Monitoring Network are used to detect and survey [112] the arrival of migrating moths. Recent research has shown that capture of male moths in pheromone-baited traps in the Prairie Pest Monitoring Network is correlated with moderate, but not low, densities of the immature stages of the diamondback moth sampled in the same fields [113]. Then exists the potential to develop commercially available pheromone-baited traps as tools that can predict the ephemeral nature of diamondback moth population densities in the prairies and inform producers of key thresholds and timing for control efforts [113].

When placed on Delta sticky traps, the artificial sex pheromone Bioplutella, marketed in Brazil, efficiently captured males of the diamondback moth and could be used for monitoring this pest [114].

3. Final remarks

As shown above, the management of pests on crucifers in Brazil has largely been dependent on synthetic pesticides, used prophylactically or in response to *P. xylostella* occurrence, although cultural practices have also played some role in the control of the diamondback moth [104]. The general lack of understanding of interactions between crucifers and their invertebrate pests and between pests and their natural enemies has resulted in a lack of alternative integrated options for growers. Growers would rely less heavily on the prophylactic and reactive application of broad-spectrum pesticides if they were provided with knowledge and training in identifying natural enemies and using economic thresholds. Furthermore, we again emphasize glucosinolates, their breakdown products, and plant volatile compounds as key components in these processes [115], which have been considered beneficial in the past and hold great promise for the future of integrated pest management.

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