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REVIEW ARTICLE

Environment polluting conventional chemical control compared to an environmentally friendly IPM approach for control of diamondback moth, *Plutella xylostella* (L.), in China: a review

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Abstract The diamondback moth, *Plutella xylostella*, is recognized as a widely distributed destructive insect pest of *Brassica* worldwide. The management of this pest is a serious issue, and an estimated annual cost of its management has reached approximately US$4 billion. Despite the fact that chemicals are a serious threat to the environment, lots of chemicals are applied for controlling various insect pests especially *P. xylostella*. An overreliance on chemical control has not only led to the evolution of resistance to insecticides and to a reduction of natural enemies but also has polluted various components of water, air, and soil ecosystem. In the present scenario, there is a need to implement an environmentally friendly integrated pest management (IPM) approach with new management tactics (microbial control, biological control, cultural control, mating disruption, insecticide rotation strategies, and plant resistance) for an alternative to chemical control. The IPM approach is not only economically beneficial but also reduces the environmental and health risks. The present review synthesizes published information on the insecticide resistance against *P. xylostella* and emphasizes on adopting an alternative environmentally friendly IPM approach for controlling *P. xylostella* in China.

Keywords *Plutella xylostella* · Biocontrol · Insecticide resistance · Management strategies

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Introduction

The diamondback moth, *Plutella xylostella*, has become one of the most destructive insect pests of *Brassica* all over the world in the past four decades. The annual cost of its management has reached approximately US$4 billion (Zalucki et al. 2012). The reasons for its continued success against modern pest management approaches include its high reproductive potential, the disrupt of or lack of natural enemies in the system, and its ability to become resistant to a wide range of toxins and growth regulators (Talekar and Shelton 1993) (Fig. 1).

China has the largest population in the world, and cruciferous vegetables make up an important part of Chinese diet. Worldwide, the production of *Brassica* increased by 39% from 1993 to 2009 with a production area of 3.4 million hectares in 2009 (FAO 2012). In 1990, the production area of cabbage and cauliflower grown in China was 0.16 million ha which increased up to 3.35 million ha by 2010. However, even with management, the area of *Brassica* vegetable crops damaged by *P. xylostella* in China increased steadily from 0.15 million ha in 1990 to 2.23 million ha in 2010 (Li et al. 2016) (Fig. 2).

Insecticides, vital part of modern era agriculture, are used to protect and increase the yield of crops by controlling different insect pests (Liu et al. 2001). Insecticides with novel mode of action and formulation have been designed to fulfill the global demand. Insecticides applied to control insect pests should not only be toxic to the target organisms but also be biodegradable and environmentally friendly (Rosell et al. 2008). Unfortunately, it is not the case; most of the insecticides also kill natural enemies of insects. Although, on the one hand, use of insecticides has increased the yield of crops, on the other hand, the intensive application has resulted an increase in resistance in insect pests, killed natural enemies of insect pests, and polluted the ecosystem (Fig. 3) (Barriuso and Koskinen 1996; Liu et al. 2001).

In China, insecticides have been widely used for the control of crucifer specialist *P. xylostella* (Talekar and Shelton 1993). Intensive use of insecticides against *P. xylostella* in high-value crops of the *Brassica* has led to an increase in the pressure of selection for resistance, especially in the tropical and subtropical regions (Talekar and Shelton 1993). Among the crop pests, *P. xylostella* was the first one to evolve resistance to DDT (Ankersmit 1953). Since then, *P. xylostella* has evolved resistance to various chemicals used for its control in the Philippines (Barroga and Morallo-Rejesus 1974), Australia (Altmann 1988), Hawaii (Tabashnik et al. 1987), Malaysia (Syed 1992), Japan (Hama et al. 1992), North America (Shelton et al. 1993), and Thailand (Kuwahara et al. 1995).

In an effort to slow the development of resistance, several insecticides from different groups are applied to control *P. xylostella* in China (Fig. 4). It has, however, recently evolved resistance to at least 79 insecticides from a variety of insecticidal classes, including carbamates, pyrethroids, organophosphates, spinosad, abamectin, and *Bacillus thuringiensis*-based products (Sun et al. 2012; Talekar and Shelton 1993). Despite the growing problem, chemical control is still considered as the major tool to manage *P. xylostella* in China. The insecticide resistance issue and eventual failure of *P. xylostella* control measures has made it difficult to economically produce *Brassica* crops in several areas of China (Liang et al. 2001).

In the current scenario, in order to reduce harmful effects of insecticides, researchers from all over the world have focused their attention on alternative control strategies. (Diez et al. 2012; Hussain et al. 2009; Liu et al. 2001; Rubilar et al. 2007; Sutherland et al. 2002), and one of the most effective and long-term environmentally safe approach is integrated pest management (IPM). In this context, the current review synthesizes published information on the insecticide resistance against *P. xylostella* and emphasizes on adopting an alternative environmentally friendly IPM approach for controlling *P. xylostella* in China.

Distribution and origin of *P. xylostella*

Plutella xylostella is considered as the most widely distributed species of Lepidoptera, occurring universally wherever Brassicaceae are grown, and causes severe damage (Fig. 1) (Talekar and Shelton 1993). Out of 21 species of the genus *Plutella* (Schrank), six have been recorded as economically important worldwide, but only *P. xylostella* is cosmopolitan in distribution (Kfir 1998).

Fig. 1 Cabbage crop damaged by *Plutella xylostella*

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Fig. 2 Map of China showing different provinces in which *Plutella xylostella* has been reported

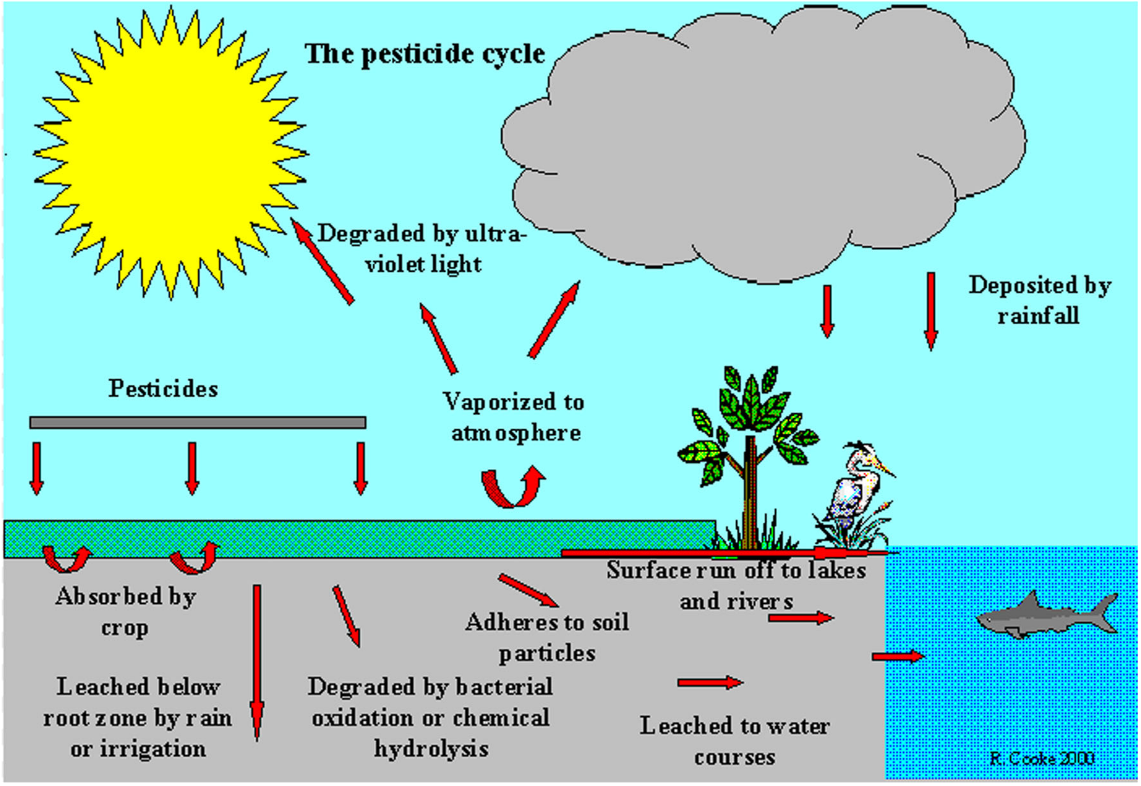

Fig. 3 An overview figure of the pesticide cycle in the environment

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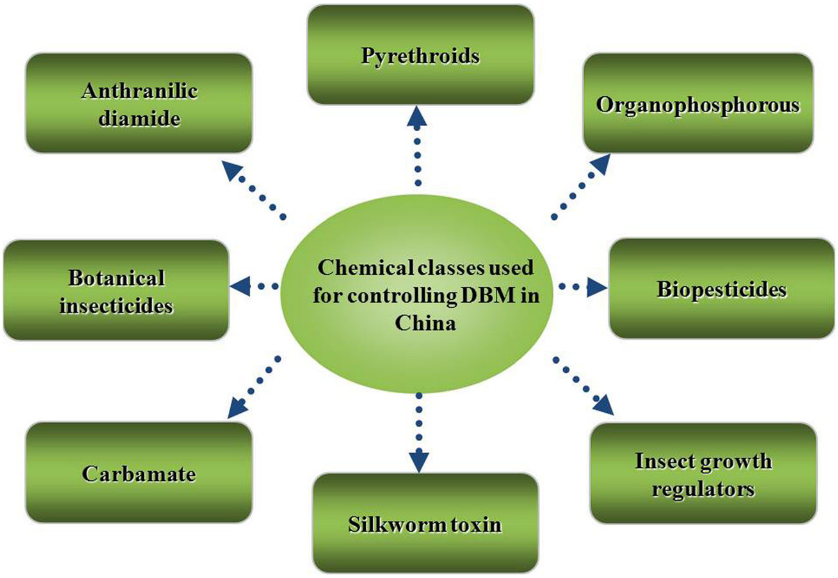

Fig. 4 An overview figure of chemical classes used for controlling *Plutella xylostella* in China

There is confusion about the geographical origin of *P. xylostella* that has been recorded to be Europe (Hardy 1938), South Africa based on the existence of natural enemies (14 parasitoids) and host plants (175) (Kfir 1998), or China (Liu et al. 2002). It is not only present in areas where *Brassica* crops are grown but also occurs in areas where the host plants exist, and among all lepidopteron, this pest has a broad distribution (Shelton 2004).

In China, the occurrence of *P. xylostella* has been found in many parts (Fig. 2) and it caused severe losses to the production of Brassica and canola (Feng et al. 2011). The populations of *P. xylostella* occurring in Northern China migrate to the area from south (Yang et al. 2015).

Recently, some climatic models have been developed to predict *P. xylostella* distribution and seasonal phenology in areas of its occasional occurrence in China. The abundance and distribution of the *P. xylostella* populations, however, is regulated by climate, availability, and quality of host plants and the presence of its natural enemies in China (Zalucki and Furlong 2011).

Biology of *P. xylostella*

The biology of *P. xylostella* in relation to ecological factors has been studied extensively in both laboratory and natural conditions. However, its biological and developmental parameters vary due to differences in host plant species (cultivated and wild crucifers; Table 1), temperature, and geographical population distribution (Alizadeh et al. 2011). *P. xylostella* is multivoltine and can produce four generations per year in temperate regions and 20 generations per year in tropical regions (Vickers et al. 2004). It is reported that in North America, three to five generations per year are produced by this pest (Harcourt 1957). This pest can develop at temperatures ranging between 4 to 38 °C under varying temperatures (Liu et al. 2002). Female *P. xylostella* are capable of laying over 200 eggs mainly on the upper surface of the leaf (Justus et al. 2000; Talekar et al. 1994). The hatching of eggs occurs after 4–8 days at 20–25 °C, and first instar larvae are leaf miners that usually feed on the spongy mesophyll of the leaves (Harcourt 1957). The late instar larvae (second, third, and fourth instar) feed on the leaf surface and consume leaves, buds, flowers, siliques, and the green outer layer of stems, and also on the developing seeds within older siliques (Sarfraz et al. 2005). Under field conditions in Canada, the average duration for the 1st to 4th larval instars was 4.0, 3.6, 3.4, and 4.2 days, respectively, with an additional 7.8–9.8 days needed for pupation (Harcourt 1957). In tropical regions, *P. xylostella* has as many as 20 generations per year, indicating rapid developmental time from the egg to adult stages.

The population dynamics of *P. xylostella* was investigated in 10 provinces of China (South, South-West, East, North, and central China) (Feng et al. 2011). In South China, more than 20 generations occur, whereas, only two to three generations commonly occur in Northeast China. In South China, an initial population peak occurs during February–March, and this spring peak is similar in size to the peak that occurs from October to November in the autumn. In Northeast China, an initial peak occurs during May–June, and this spring peak is higher than the autumn one that occurs in August–September (Feng et al. 2011). Development and survival vary greatly depending on quality of food, quantity of adult feeding, differences in host plant cultivar, and sources of carbohydrate (Alizadeh et al. 2011; Winkler et al. 2005).

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Table 1 Examples of host plants of *Plutella xylostella* in China

Type of plant	Common name(s)	Species/cultivar	Selected reference(s)
Cruciferous crops	Chinese cabbage	*Brassica rapa* L.var. *pekinensis*	(Li et al. 2016)
	Rapeseed	*Brassica napus* L.	(Wang et al. 2014)
	Cauliflower	*Brassica oleracea* L. var. *botrytis*	(Jiang et al. 2015)
	Radish	*Raphanus sativus* L.	(Li et al. 2016)
	Pak choi	*Brassica chinensis* L.	(Jiang et al. 2015)
	Broccoli	*Brassica capitata* L.	(Tang et al. 2014; Yi et al. 2015)
	Cabbage	*Brassica oleracea* L. var. *capitata*	(Huang et al. 2014; Jiang et al. 2015)
	Brown mustard	*Brassica juncea* (L.)	(Huang et al. 2014; Jiang et al. 2015)
Wild plants	Rorippa	*Rorippa indica* (L.) Hiern	(Niu et al. 2014)
	Hairy bittercress	*Cardamine hirsuta* L.	(Niu et al. 2014)
	Flixweed	*Descurainia sophia* (L.)	(Niu et al. 2014)
	Shepherd's purse	*Capsella bursa-pastoris* (L.)	(Niu et al. 2014)
	field penycress	*Thlaspi arvense* L.	(Niu et al. 2014)
	Bright and bronzy	*Cardamine macrophylla* Willd.	(Niu et al. 2014)
	Chinese violet cress	*Orychophragmus violaceus* (L.) O.E. Schulz	(Niu et al. 2014)

Resistance of *P. xylostella* to various insecticides in China

Resistance to abamectin

Avermectins are known to have broad spectrum of activity against insect pests, and among avermectins, abamectin has been used widely for the control of insect pests (Lasota and Dybas 1991). In the recent years, it has been intensively used for the control of *P. xylostella* in China, leading to its failure as an effective insecticide (Pu et al. 2010). Abamectin is developed by fermentation of a soil bacterium *Streptomyces avermitilis* and acts on the glutamate-gated chloride channel (Cully et al. 1996). The resistance mechanism of *P. xylostella* to abamectin involves different factors, including target site mutation, reduced cuticle penetration, and an increase in detoxification enzymes (Qian et al. 2008; Wu et al. 2002; Zhou et al. 2011).

In 1999, a low level of resistance was reported in Guangdong province (Xia et al. 2001) and a progressive increase was observed in the resistance of abamectin to *P. xylostella* with a high level of resistance reported in 2013 in the same province. The same phenomenon was also observed in other provinces like Yunnan and Hunan, where a lower resistance level was reported initially, but it significantly increased after continuous application of abamectin (Table 2) (Jiang et al. 2015; Xia et al. 2014).

Resistance to chlorantraniliprole

Chlorantraniliprole is one of the new classes of insecticides that are highly effective against lepidopteron insect pests especially *P. xylostella* (Chen et al. 2010). It selectively binds to ryanodine receptors (RyR) in muscle and nervous tissue, resulting in an uncontrolled release of calcium from internal stores in the sarcoplasmic reticulum. The calcium release within the cells leads to feeding cessation, lethargy, muscle paralysis, and ultimately death of target organisms (Cordova et al. 2006; Sattelle et al. 2008). The resistance mechanism of *P. xylostella* to chlorantraniliprole involves increased activity of cytochrome P450, carboxylesterase, and glutathione S-transferases and a point mutation in RyR (Guo et al. 2014; Wang and Wu 2012).

In China, since 2008, chlorantraniliprole has been introduced to control *P. xylostella*. The toxicity tests on the majority of field populations of *P. xylostella* showed a low level of resistance to chlorantraniliprole (Table 2) (Chen et al. 2010; Hu et al. 2010; Wang et al. 2010). Nevertheless, resistance against chlorantraniliprole in populations of China presents a great risk to the insecticide effective life as high level of resistance was reported in Guangdong province, China (Hu et al. 2010; Wang and Wu 2012).

Resistance to cyantraniliprole

Cyantraniliprole, an anthranilic diamide, is an *o*-amino benzamide insecticide having a cyano group instead of the four-halo substituent of the former anthranilic diamide chlorantraniliprole (Feng et al. 2010). It is reported to have a broad spectrum of activity against the insects as compared to chlorantraniliprole (Chai et al. 2010). *P. xylostella* showed a high level of resistance to cyantraniliprole in a population maintained up to 26 generations of selection compared with field and susceptible population (Liu et al. 2015).

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Table 2 Field resistance of *Plutella xylostella* to insecticides

Chemical class	Chemical	Mechanism	Region of China	Resistance level	Citation
Organophosphates	Phoxim	MFO, GST, esterase	Guangdong	Low	(Zhou et al. 2011)
Pyrethroids	Beta-cypermethrin	–	Yunnan, Hunan, Guangdong	High	(Wei et al. 2012; Yin et al. 2011; Zhou et al. 2011)
Anthranilic diamides	Chlorantraniliprole	MFO/esterase	Guangdong	High	(Hu et al. 2014; Wang and Wu 2012)
Phenylpyrazoles	Fipronil	MFO/esterase	Guangdong	High	(Zhou et al. 2011)
Chlorfenapyr	Chlorfenapyr	–	Guangdong, Hubei, Henan	No field resistance	(Jiang et al. 2015; Xia et al. 2014)
Diafenthiuron	Diafenthiuron	–	Guangdong, Hubei, Henan	No field resistance	(Jiang et al. 2015; Xia et al. 2014)
Benzoylureas	Chlorfluazuron	MFO/esterase	Guangdong	No field resistance	(Jiang et al. 2015)
			Hubei and Henan	Low to High	(Xia et al. 2014)
Avermectins	Abamectin	MFO/esterase	Yunnan, Hunan, Guangdong	High	(Jiang et al. 2015; Xia et al. 2014)
Spinosyns	Spinosads	Not MFO or esterase	Guangdong, Hubei, Henan	Low to moderate	(Jiang et al. 2015; Xia et al. 2014)
Microbial disruptors of insect midgut membranes	*Bacillus thuringiensis*	No binding to gut membrane	Guangdong, Hubei, Henan	High	(Jiang et al. 2015; Xia et al. 2014)

Resistance to flubendiamide

Flubendiamide, an anthranilic diamide, selectively activates RyR, inducing ryanodine-sensitive cytosolic calcium transients that are independent of the extracellular calcium concentration (Ebbinghaus-Kintscher et al. 2006). It controls *P. xylostella* effectively when applied as a larvicide (Hirooka et al. 2007; Nauen 2006; Tohnishi et al. 2005). Moderate- and high-level resistance to flubendiamide was identified in laboratory-selected and two field-collected strains of *P. xylostella* (Yan et al. 2014).

Resistance to beta-cypermethrin

Pyrethroid insecticides act by modifying the gating kinetics of the *para*-type sodium channels in insect neurocytes by slowing both the activation and inactivation of the channels (Lund and Narahashi 1983). Modifications in the sodium channel structure results in lower sensitivity to pyrethroids, and reduced target-site sensitivity of sodium channels is known to be one of the major mechanisms of pyrethroid resistance and is referred to as knock-down resistance (*kdr*) (Soderlund and Knipple 2003).

In China, a synthetic pyrethroid, namely, beta-cypermethrin, has been used on frequent basis to control *P. xylostella*. However, monitoring results of field populations showed different resistance levels to beta cypermethrin. *P. xylostella* showed a low level of resistance to beta-cypermethrin in Liaoning Province of China (Yang et al. 2011). A high level of resistance was observed in the populations of *P. xylostella* from Yunnan, Hunan, and Guangdong provinces of China (Table 2) (Wei et al. 2012; Yin et al. 2011; Zhou et al. 2011). The possible reason may be that beta-cypermethrin has been still extensively used as an admixture with other insecticides in China. Based on the above results, beta-cypermethrin may need to be suspended for controlling *P. xylostella* in China due to high resistance.

Resistance to spinosad

The spinosyns, a family of secondary metabolites from *Saccharopolyspora spinosa*, have a broad spectrum of activity against insect pests (Thompson et al. 2000). Spinosyns act on a binding site on the nicotinic acetylcholine receptors (nAChRs) that is distinct from that targeted by neonicotinoid (Sparks et al. 2012).

Spinosad is considered as an effective insecticide to control *P. xylostella* in China (Jiang et al. 2015). A low to moderate level of resistance was observed to spinosad in Hunan, Hubei, and Guangdong provinces (Table 2) (Jiang et al. 2015; Xia et al. 2014).

Resistance to fipronil

Fipronil, a phenyl pyrazole insecticide, is considered as highly effective against both chewing and piercing sucking insects

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(Moffat 1993). It acts by blocking the insect GABA-gated chloride channel or GABA receptor (Buckingham et al. 1994; Cole et al. 1993).

Fipronil was first introduced in China in the 1990s. At the beginning, the populations of *P. xylostella* were susceptible to fipronil (Zhang et al. 2000), a low level of resistance was observed in Hunan Province (Huang et al. 2008), and after that a progressive increase was observed in resistance to fipronil from 1999 to 2009 in Guangdong province (Table 2) (Zhou et al. 2011).

Resistance to *Bacillus thuringiensis*

Bacillus thuringiensis (Bt), a spore-forming bacterium, is a common invertebrate pathogen. Highly toxic crystal (Cry) proteins produced by Bt are used as a source of microbial pesticides, and its genes have been transferred into crops to show resistance to insect pests (Schnepf et al. 1998). The sustainable exploitation of Bt has been a major challenge due to the development of resistance evolution by major pest species (Ayra-Pardo et al. 2015). Until now, three lepidopteron pest species have been reported to evolve substantial resistance to Bt sprays in the field (Tabashnik et al. 1990).

P. xylostella has also evolved resistance to Btk, Cry1Ab, and Cry1Ac in China. At the beginning, a low level of resistance to Btk was identified in field-collected populations from Guangdong, China (Li et al. 1997). A progressive increase in resistance development was observed to Btk with a high level of resistance found in Hunan, Hubei, and Guangdong provinces (Table 2) (Jiang et al. 2015; Xia et al. 2014). Cry1Ab and Cry1Ac showed a high level of resistance in the field populations of Guangdong in 2003 (Wang et al. 2005).

Resistance to phoxim

Phoxim, an organophosphorus pesticide, is one of the most widely used pesticides in China (Wang et al. 2015). It acts by irreversibly binding to acetylcholinesterase (AChE) and inhibits its activity, which leads to neurotransmitter acetylcholine (ACh) accumulation in synaptic clefts, then insect convulsion takes place and eventual death of the insect occurs because the nervous excitement cannot be terminated (Shang et al. 2007).

A low level of resistance to phoxim was observed in Guangdong province, and it was maintained for a relatively long time. The reason of this was probably the light instability of phoxim, which relieves *P. xylostella* from a continuous selection pressure (Table 2) (Zhou et al. 2011).

Resistance to chlorfenapyr

Chlorfenapyr, a pro-insecticide, is activated by oxygenases to a toxic form identified as AC-303268 which is a mitochondrial un-coupler (Black et al. 1994). AC-303268 functions to uncouple oxidative phosphorylation in the mitochondria, resulting in disruption of ATP production and loss of energy leading to cell dysfunction and subsequent death of the organism. As this molecule is less toxic to mammals, so it is classified as "slightly hazardous" by WHO (Tomlin 2000).

Chlorfenapyr is widely used against a variety of insect and mite pests (Pimprale et al. 1997; Sheppard and Joyce 1998). *P. xylostella* populations were also found susceptible to chlorfenapyr in Hunan, Hubei, and Guangdong provinces (Table 2) (Jiang et al. 2015; Xia et al. 2014). The reason might be that chlorfenapyr has not been used as frequently as other insecticides (Jiang et al. 2015).

Resistance to chlorfluazuron

Chlorfluazuron, a benzoylphenyl urea compound, acts as a chitin synthesis inhibitor and is used to control lepidopterous and coleopterous larvae. It is reported to be less toxic to mammals and showed no cross resistance with conventional insecticides (Ishaaya 1993). Chlorfluazuron is considered to be a better insecticide for the pest control because it has a relatively long half-life in insect bodies with a slow metabolism and elimination rate (Sammour et al. 2008).

Chlorfluazuron has been used to control *P. xylostella* in China from the last two decades (Xia et al. 2014). Chlorfluazuron was very effective in controlling *P. xylostella* in Guangdong province and showed high toxicity (Table 2) (Jiang et al. 2015), whereas in Hunan and Hubei provinces low to high resistance was observed (Xia et al. 2014).

Resistance to diafenthiuron

Diafenthiuron, a thiourea compound, acts by inhibiting or enhancing biochemical sites such as respiration (Ishaaya et al. 2001). Diafenthiuron is considered as a viable tool because it inhibits mitochondrial action and energy metabolism (Ruder and Kayser 1992).

Diafenthiuron has been used to control *P. xylostella* since the twentieth century (Xia et al. 2014). It showed high toxicity to *P. xylostella* populations of Guangdong, Hubei, and Henan provinces (Table 2) (Jiang et al. 2015; Xia et al. 2014).

Environmentally friendly, integrated pest management, approach for controlling *P. xylostella* in China

Biological control

Biological control-based integrated pest management system involving parasitoids and predators also plays an important role in controlling *P. xylostella* (Liu and Yan 1998; Ooi 1992; Saucke et al. 2000; Talekar and Shelton 1993; Verkerk and Wright 1996).

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The biological control of *P. xylostella* in a classical way started in 1936 when the successful introduction of *Diadegma semiclausum* (Hymenoptera: Ichneumonidae), a larval-pupal parasitoid, and *Diadromus collaris* (Hymenoptera: Ichneumonidae), a pupal parasitoid, was done from the UK to New Zealand (Talekar and Shelton 1993), leading to further introductions of these species from New Zealand into Malaysia (Ooi 1992), Indonesia (Vos 1953), and Australia (Wilson 1960). In Taiwan, *D. semiclausum* was imported from Indonesia and established successfully (Talekar et al. 1992), and provided stock material for further successful introductions into the mainland of China (Talekar 2004), India (Chandramohan 1994), Philippines (Ventura 1997), Vietnam, Laos, and Kenya (Löhr et al. 2006).

All stages of *P. xylostella* are attacked by various parasitoids and predators. Over 135 parasitoid species have been reported worldwide (Delvare et al. 2004). Among these, the most commonly occurring ones include six egg parasitoid species, 38 species of larval parasitoids, and 13 pupal parasitoids (Lim 1986a). Preliminary surveys for the insect parasitoids of *P. xylostella* were conducted on the mainland of China in Hubei (Lu 1983), Guangdong (Chen et al. 1987), Beijing, and Zhejiang (Ke and Fang 1982) provinces for the insect parasitoids of *P. xylostella.* A total of almost eight parasitoid species, such as *Cotesia plutellae*, *Oomyzus sokolowskii*, and *D. collaris* are reported as the main parasitoids of larval, larval-pupal, and pupal parasitoids of *P. xylostella*, respectively (Liu et al. 2000) (Table 3).

Egg parasitoids

The egg parasitoids of genera *Trichogramma* and *Trichogrammatoidea* (Hymenoptera: *Trichogrammatoidea*), due to the non-host specific nature, are considered as insufficient natural control agents (Goulet and Huber 1993). In addition, to utilize them in biological control initiatives requires frequent inundated releases (Talekar and Shelton 1993). Parasitization of *P. xylostella* eggs by *Trichogramma* and *Trichogrammatoidea* in the field has been recorded from China (Huang et al. 2002; Liu et al. 2000). *P. xylostella* eggs were attacked by five species of *Trichogramma* and *Trichogrammatoidea* parasitoids at an ecological farm in South China where integrated pest management techniques such as pheromone traps and *B. thuringiensis* have been adopted since 1994 (He et al. 2002). Parasitization of *P. xylostella* eggs by 29 species of *Trichogramma* and *Trichogrammatoidea* was tested in the laboratory and 23 of these egg parasitoids were able to parasitize eggs of *P. xylostella* (Guo et al. 1999).

Table 3 Hymenopterous parasitoids of *Plutella xylostella* recorded from Hangzhou, China

Stages attacked	Species	Family
Egg	*Trichogramma chilonis* Ishii	Trichogrammatidae
Larva	*Cotesia plutellae* Kurdjumov	Braconidae
	Microplitis sp.	Braconidae
Larva-pupa	*Oomyzus sokolowskii* Kurdjumov	Eulophidae
Pupa	*Diadromus collaris* (Gravenhorst)	Ichneumonidae
	Itoplectis naranyae (Ashmead)	Ichneumonidae
	Exochus sp.	Ichneumonidae
	Brachymeria excarinata Gahan	Chalcididae

Adopted and modified from (Liu et al. 2000)

Larval parasitoids

Larval parasitoids are predominant and have the maximum control potential for *P. xylostella* (Munir et al. 2015; Talekar and Shelton 1993). The larval parasitoids of hymenopteran genera *Cotesia* (Braconidae), *Microplitis* (Braconidae), and *Diadegma* (Ichneumonidae) are known as the most effective larval parasitoids of *P. xylostella* (Lim 1986a; Talekar and Shelton 1993). Almost 20 classical biological control introductions used the larval parasitoid *Cotesia vestalis* for the control of *P. xylostella*, and many of them have been successful (Delvare et al. 2004; Talekar 2004). Additionally, this parasitoid is widely distributed in nature than *D. semiclausum*, and it has been reported to attack *P. xylostella* in many parts of the world such as Taiwan, Vietnam (Talekar 2004), Japan (Alvi and Momoi 1994), and Malaysia (Ooi 1992), with no records of introductions. Although in South Africa (Kfir 1998), Japan (Talekar 2004), Australia (Furlong and Zalucki 2007), and North Korea (Furlong et al. 2008) the larval-pupal parasitoid *O. sokolowskii* was not introduced, it has also been recorded in these countries. In China, parasitization by *C. vestalis* and *D. semiclausum* on the nutritional physiology of *P. xylostella* larvae resulted in a significant decrease in the rates of feeding, growth, excretion, assimilation, and respiration (Huang et al. 2008).

Cotesia plutellae is considered the most promising biological control agent in China, and in the suburbs of Hangzhou, Zhejiang, China, *C. plutellae* was the main parasitoid of *P. xylostella*, active all around the year (Liu et al. 2002). All the instars of *P. xylostella* could be parasitized by *C. plutellae*, but second and third instars are preferred (Shi et al. 2002). *C. plutellae* parasitized 4- to 15-fold more *P. xylostella* on Chinese cabbage than common cabbage, and the plant volatiles from the Chinese cabbage were also more attractive to *C. plutellae* than the common cabbage. These results showed that plant and host volatiles play an important role in mediating host selection (Liu and Jiang 2003).

Pre-pupal and pupal parasitoids

Occasionally, some species of *Pteromalus* (Hymenoptera: Pteromalidae) species parasitize *P. xylostella* pupae (Chauhan et al. 2002). The pupal parasitoids of *P. xylostella* including *D. collaris* and *D. subtilicornis* have been reported to be widely distributed in nature (Delvare et al. 2004). The pupal parasitoid

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D. collaris has been introduced into many countries after its initial introduction in New Zealand (Delvare et al. 2004). In China, only a few of the genus *Diadromus* (*Ichneumonidae*) also provide significant control (Liu et al. 2000). *D. collaris* is an effective pupal parasitoid of *P. xylostella* in China (Shi et al. 2002). When *D. collaris* was allowed to parasitize on *P. xylostella* pupae of different ages, the female *D. collaris* preferred pupae that were in the first half of their development. If there is no other choice, then it will also oviposit on older pupae of the host, but this will decrease the survival of *D. collaris* (Wang and Liu 2002).

Predators

Predators are also known to cause mortality of pest populations and are considered as an important factor in the regulation of pest populations (Symondson et al. 2002). Until now, majority of studies have focused on parasitoids and predators have received less attention (Furlong et al. 2004; Ma et al. 2005). Spiders are found in abundance in grain crops and are reported as an important group of predators (Ma et al. 2005). Although predators are considered as natural enemies of the pest population, little is known about the feeding rate of the predator and the effect on *P. xylostella* (Furlong et al. 2004).

Sex pheromone as a mating disruptant

The use of sex pheromones as mating disruptant is considered as an important method, due to the specificity and low toxicity to non-target organisms, among various control alternatives (Philips et al. 2014). The first use of sex pheromones as a mating disruptant was to control pink bollworm, *Pectinophora gossypiella*, in 1970, and now the female sex pheromones of *P. xylostella* are also commercially available (Baker 2008). In China, populations of *P. xylostella* have been suppressed and monitored by sex pheromones for more than three decades (Ying 1986). The major components of *P. xylostella* sex pheromones are (Z)-11-hexadecenal, (Z11-16 Ald), and (Z)-11-hexadecenyl acetate (Z11-16 Ac), but an addition of (Z)-11 hexadecenol (Z11-16 OH) in the bait improved its efficiency in the field (Chou et al. 1977; Koshihara and Yamada 1980; Tamaki et al. 1977). Sex pheromones also effectively controlled *P. xylostella* in the greenhouse (Hou et al. 2001).

Field studies showed that the efficiency of sex pheromones can be improved by manipulating its component ratios and dose rates (Wang et al. 2013), deployment of wing-shaped traps, and the use of half-bell-shaped septum dispensers (Kang et al. 2011). Sex pheromones should also be applied in an un-cultivated area of crucifer crops. In order to make the control effective, fields of crucifer crops should be flat and without strong winds, so that the pheromone odor can linger in the crucifer crop fields (Nemoto et al. 1992; Ohbayashi et al. 1990). Although pheromones have become well established in some integrated pest management programs, there are several limitations to these tools, the most limiting of which is cost (Baker 2008).

Cultural control

Cultural control is considered to play a vital role in management programs of *P. xylostella* having the most important methods like crop rotation, trap cropping, and plant resistance (Philips et al. 2014).

Crop rotation

Rotations to non-*Brassica* and clean cultivation practices, although not novel, are the best management tactics which can be employed in China currently for control of *P. xylostella*. Movement of *P. xylostella*-infested plants, especially transplants, from one area will often lead to uncontrollable problems (Shelton et al. 1993), but this can be managed. More difficult to manage is the spatial separation of plantings and crop-free periods. In the broccoli-growing regions of Mexico, an overall management program which included a crop-free period has been effective, but as enforcement of this crop-free period has been relaxed, problems have resurfaced. When three different cropping systems including continuous cropping rotations with either rice or fallow were compared, the highest population was observed in the continuous cropping field, whereas the population of *P. xylostella* was reduced significantly in the two other rotations because of breaking the availability of the host plant (Feng et al. 2011).

Trap cropping

Trap cropping, a technique practiced before the advent of modern insecticides, is now making a comeback in countries like India (Shelton et al. 1997). The main characteristic of the crop to be used as a trap crop is that it should provide more attraction as a food source and oviposition site as compared to the host plant (Satpathy et al. 2010). In a dual choice test of plants, *P. xylostella* preferred to lay its eggs on *Barbarea vulgaris* rather than cabbage indicating that the wild crucifer *B. vulgaris* has the potential to serve as a dead-end-trap crop for controlling *P. xylostella* (Lu et al. 2004). Collard crop was preferred for oviposition as *P. xylostella* laid up to 300 times more eggs than the cabbage (Badenes-Perez et al. 2004). Females of *P. xylostella* preferred to lay eggs on Indian mustard, and the larval survival was found very low (Charleston and Kfir 2000). As the trap crops like mustard *Brassica juncea* (L.) Czernj. & Coss., collards (*Brassica oleracea* var. *acephala*), and yellow rocket *B. vulgaris* (R.Br) showed efficient attraction ability of *P. xylostella*, so it is recommended that these crops should be used as trap crops for controlling *P. xylostella*.

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Use of plant resistance

The valuable tactic to control the insect pests is plant resistance as it does not need any special action from growers and develops a cheap and practical input in the integrated control system (Lim 1986b). The production of resistant varieties via biotechnology is considered as an important tool in controlling *P. xylostella* (Philips et al. 2014). For example, the screenhouse and field trials showed that transgenic Bt-*Brassica* crops (cabbage and cauliflower) not only suppressed the population of *P. xylostella* (Furlong et al. 2013; Ramachandran et al. 1998), but are also safe for the biological control agents as these transformed crops do not have direct effect on parasitoids and predators (Furlong et al. 2013). The transgenic *B. juncea* expressing cry1Ac gene showed that the transgenic plants were more resistant to 2nd instar larvae of *P. xylostella* as compared to the non-transgenic plants (Kamble et al. 2013). A comparative study on transgenic Bt cabbage and non-transgenic cabbage in the laboratory showed that adult and larvae of *P. xylostella* were attracted at an equal rate on both types of plants and after hatching 100% mortality of 1st instar larvae was observed on transgenic cabbage plants (Kumar 2004). Although transgenic Bt-*Brassica* crops have successfully controlled *P. xylostella* populations, it is difficult to release these crops in field due to regulatory and liability issues (Furlong et al. 2013).

Monitoring of *P. xylostella* population

Forecasting and monitoring for pests are considered as important parts of IPM strategy. Monitoring of pests is conducted by the use of various monitoring tools including pheromone traps, light traps, colored sticky traps, pitfall traps, and suction traps (Prasad and Prabhakar 2012). In order to monitor the insect populations, the use of traditional light traps has been widely adopted (Kato et al. 2000) and light trap sampling showed more efficiency for lepidopteron population dynamics (Raimondo et al. 2004). For monitoring the populations of *P. xylostella* in the fields, the sex pheromone traps and yellow sticky traps are considered as valuable tools (Saito et al. 1990). A greater number of *P. xylostella* adults were caught by yellow sticky trap as compared to light trap and a pheromone trap (Saito et al. 1990). As the traps of pheromone are sensitive and species-specific, more male moths can be trapped even when the population is low (Sharov et al. 2002).

Conclusions

P. xylostella has consistently remained the main destructive insect pest of crucifer vegetables around the world. The fields in which insecticides are applied heavily and on a frequent basis are supposed to have major outbreaks of *P. xylostella*. In most regions of China, the major reason of increasing pest status of *P. xylostella* is rapid development of resistance to insecticides and lack of effective natural enemies. Although it is not easy to manage the resistance of *P. xylostella*, the development of insecticide resistance can be managed by reducing insecticide selection pressure in different manners. Growers should also be trained in the matter of selecting proper insecticides depending on the season and developmental stage of crucifer crops, which may have reduced selection pressure of insecticides on *P. xylostella*. This aspect of resistance could be an area for future research. In order to reduce the insecticide resistance to *P. xylostella*, it is important to introduce IRM strategies to farmers. Monitoring the status of insecticide resistance is essential for predicting the insecticide control failure in combination to integrated pest management in the future. The selection pressure of insecticides can also be reduced by introducing alternate *P. xylostella* control methods. Many effective control measures like cultural control, sex pheromone traps, and release of parasitoids should be integrated for controlling *P. xylostella*. For any effective management strategy whether it involves habitat management, biological control, or integration of different control measures, up to date knowledge of pest and parasitoid behavior and population dynamics, as well as cautious evolutionary interpretation of tritrophic relationship in a particular agroecosystem, is crucial.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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