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Management of Diamondback Moth, *Plutella xylostella* (Lepidoptera: Plutellidae): a Lesson from South East Asia for Sustainable Integrated Pest Management

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Abstract: The diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae) is the greatest threat to crucifer through out the world including Pakistan, sometime causing more than 90% crop loss and estimated cost over US$ 1 billion annually. Prior to the introduction of synthetic insecticides diamondback moths were never reported as the major pests of crucifers, however with widespread use of synthetic insecticides on crucifer important natural enemies were eliminated which led to continue use of synthetic insecticides and eventual insecticide resistance and control failure.

This review provides a global overview of the biology and ecology of diamondback moth including past, present and perspective future management strategies with special reference to Pakistan.

Key words: *Plutella xylostella, Bacillus thuringiensis* , insecticide resistance, control failure, *Bt* crops, IPM.

Distribution and economic importance: *Plutella xylostella* is cosmopolitan in distribution (Salinas, 1986) although it is generally thought to have originated in the Mediterranean region (Waterhouse and Norris, 1987). More recently, Kfir (1998) has suggested that *P. xylostella* might have originated in Southern Africa due to rich and diverse fauna of *P. xylostella* parasitoids, the large number of indigenous brassicas and the arrhenotokous form of the *P. xylostella* parasitoid, *Diadromus collaris* Grav. It has been recorded throughout temperate and tropical zones, as far north as Iceland (60 °N) and far south as Newzealand (45 °S) (Ooi, 1986). Studies have shown that movement of *P. xylostella* occurs mainly through imported cabbage (Tan and Lim, 1985).

Plutella xylostella is the most destructive pest of cruciferous plants throughout the world (excluding Europe) sometimes causing more than 90% crop loss (Verkerk and Wright, 1996) and inflicts more than US $ one billion in losses per year (FAO, 1992). In the tropics and sub-tropics, *P. xylostella* can cause damage throughout the year except for a brief period during the rainy season (Talekar and Lee, 1985). The larvae of *P. xylostella* feed on all above ground parts of the plant thereby reducing yield and quality and thus marketability of the produce (Talekar, 1996).

Lack of natural enemies in many non-indigenous areas, especially of parasitoids, its ability to migrate long distances and its high rate of fecundity are considered to be the major causes of the high pest status of *P. xylostella* in most parts of the world (Lim, 1986). The widespread use of synthetic insecticides on high value crucifer crops has resulted in high levels of resistance in *P. xylostella* populations (Talekar and Shelton, 1993).

Host range: The host range for *P. xylostella* is limited to crucifers that contain mustard oils and their glucosides (Hillyer and Thorsteinson, 1971). Many glucosinolates stimulate feeding in *P. xylostella* but two of these, 3-butenyl and 2-phenyl ethyl, are toxic at high concentrations (Nayar and Thorsteinson, 1963). The glucosides sinigrin, sinalbin and glucocheirolin act as specific feeding stimulants for *P. xylostella* and 40 plant species containing one or more of these chemicals serve as hosts, including cabbage, broccoli, cauliflower, collards, rapeseed, mustard and Chinese cabbage. Non-host plants may contain these stimulants but also contain feeding inhibitors or toxins (Gupta and Thorsteinson, 1960a). Certain chemicals such as sulfur-containing glucosinolate or its metabolites, allyl isothio-cyanates act as oviposition stimulants (Gupta and Thorsteinson, 1960b). While Pivnick *et al.* (1990) reported that male sexual maturation results from exposure to host plants. Alternate weed hosts are especially important in maintaining the *P. xylostella* populations in temperate countries in spring before cruciferous crops are planted (Talekar and Shelton, 1993).

Biology and ecology: *Plutella xylostella* adults rest on the host plant during the daytime and become more active just before dusk (Harcourt, 1957). Mating occurs during first 4-15 hours following emergence (Pivnick *et al.*, 1990) with a peak between 1 and 2 hours of scotophase (Ohira, 1979). Mating success of *P. xylostella* can vary greatly, some males may mate with more than 10 females (Yamada, 1979), and mating success of both sexes may be influenced by age (Yamada, 1979) size (Uematsu, 1992), production of sex pheromone (Chow *et. al.* 1986) and exposure to host plant (Pivnick *et al.* 1990). In response to emission of female sex pheromone during the scotophase (Pivnick *et al.* 1990), the male walks in front of the female, while vigorously fanning its wings (Ashihara, 1977). Male response to female sex pheromone was found to vary among populations in the field but did not differ between susceptible and insecticide resistant populations in the laboratory (Maa, 1986). During mating, the pair faces in opposite directions and hangs downwards, the female above, the male below (Chelliah and Srinivasan, 1986). Females start laying eggs soon after mating (Talekar and Shelton, 1993).

The oviposition rate is the highest in evening, 24 to 48 hours after mating (Abro *et al.*, 1992). The eggs are yellowish white to yellowish green (Chelliah and Srinivasan, 1986), cylindrical to oblong, with average dimensions of 0.48 x 0.25 mm (Bhalla and Dubey, 1986) and are laid mainly on the lower surface of the leaves (Abro *et al.*, 1992). A few eggs are laid on stems and leaf petioles (Harcourt, 1957). The maximum recorded number of eggs laid by a single female is 451 (Marsh, 1917). The period from oviposition to hatching ranges between 2.1 days at 26.4 2.7 °C and 86 14% RH (Wan, 1970) to 11 days at 15-26 °C and 60-90% RH (Kanervo, 1936). Just before hatching the eggs darken (Harcourt, 1957) and soon after emergence neonate larvae start crawling and making “sensing” movements with the head. After stimulation from others, larvae start to feed (Salinas, 1984) and to mine into spongy mesophyll tissue (Harcourt, 1957; Talekar and Shelton, 1993). Isolated larvae tend to starve due to lack of intra-specific stimulus (Salinas, 1984).

The first instar larvae *P. xylostella* are light green in colour with a dark head and *ca* 1 to 1.7 mm. in length. (Ho, 1965). The head capsule width is *ca* 0.16 mm, 0.26 mm 0.38 mm and 0.63 mm for first to fourth instar larvae respectively.

The first instar larvae complete moulting within feeding mines (Talekar and Shelton, 1993). Early second instar larvae emerge and feed from the lower surface of leaves, chewing irregular patches in the leaves and eventually consuming all leaf tissues except the veins and the upper epidermis creating the "window effect" characteristic of *P. xylostella* (Harcourt, 1957; Talekar and Shelton, 1993). Prior to each moult, the larvae first constructs a loose silken web adhering to leaf surface beneath which larvae moults (Ho, 1965). This also forms a sail for migration on the wind away from source of disturbances or from places where food is scarce (Wu, 1968). The newly moulted second to fourth instar larvae are pale green with a white head (Ho, 1965). Third and fourth instar larvae do the most damage as they consume a greater amount of leaf matter compared with other instars (Salinas, 1972). Fourth instar larvae destined to be males can be distinguished by the fifth abdominal segment as it lighter in colour than adjacent segments due to presence of light coloured, male gonads (Liu and Tabashnik, 1997).

Larval development varies from 5-30 days depending on the ambient temperature. It is followed by the pre-pupal and pupal stages, which may last 4-15 days (Harcourt, 1957; Waterhouse and Norris, 1987). When fully grown, the larvae frequently migrate to older and lower leaves nearer the ground (Chua and Lim, 1977) and spin a loose silken cocoon about 9 mm long (Hill, 1983). During the pre-pupal stage, larval coloration often changes from green to pink. The thoracic diameter increases while abdominal length decreases, wing development commences as well as modification to the head appendages (Robertson, 1939). The pre-pupae develop into pupae within 1-3 days at 20 °C (Salinas, 1972). When first formed, the pupa is green but gradually becomes light brown with dark markings. The pupa becomes almost black immediately before emergence. At the pupal stage, the sex of *P. xylostella* can sometimes be determined by examination of the genital openings (Robertson, 1939). The female pupa also has a greater wet and dry weight (Atwal, 1955).

The adult moth is slender, greyish brown in colour with a wing expanse of 13-17 mm. Wing expansion in male is smaller in size compared with female (Ho, 1965). Each wing has three lobe-like median yellow-white stripes that form a characteristic diamond-shaped pattern giving rise to the common name of the moth. Moths can easily be sexed by the pattern of the "diamond". (Atwal, 1955). The male also has a broad cream coloured dorsal stripe from base to near tornus often edged with black towards disk, whereas in females this stripe is much less distinct and often merged in the general background colour (Robertson, 1939).

Temperature, food availability (Wang, 1983) and rainfall (Talekar and Lee, 1985) are important factors affecting *P. xylostella* abundance. The development time from egg to adult decreases with increase in temperature (Abro *et al.*, 1992). In Malaysia, for example, *P. xylostella* takes *ca*15 days to complete its life cycle in the hotter lowland areas (monthly maximum temperature 26-28°C) compared with *ca* 26 days in cooler upland areas (monthly maximum temperature 20-24°C) resulting in 24 and 14 generations per annum respectively (Ooi, 1986). The development of *P. xylostella* is not reported to be greatly affected by fluctuations in relative humidity (Sivapragasam *et al.*, 1984) but food quality affects both the developmental period and fecundity. For example, larvae reared on mature cabbage leaves were observed to spend longer as larval and pupal stages compared with younger leaves (Atwal, 1955). Whereas larvae reared on white or young green cabbage leaves laid significantly more eggs compared with those reared on green mature leaves (Atwal, 1955). Slower development is associated with higher death rates (Atwal, 1955) while higher temperature results in decreased numbers of eggs laid by female (Abro *et al.*, 1992).

Species of *Plutella* genus: Five economically important species of *Plutella* (Sch.) have been recorded in the world, all of which are pests of brassicas. Except for *P. xylostella*, which has become cosmopolitan, the geographic distribution of these species is limited (Kfir, 1998). For example:

P. annulatella (Curt.) in Finland.
P. antiphona (Mey.) in Newzealand.
P. armoraclae (Bus.) in Colorado.
P. porrectella (L.) in Ontario, Canada.
P. balanopis (Mey.) in Southern Africa.

The highest number of *Plutella* species has been recorded in Americas; in addition to *P. xylostella*, 7 species in South America mainly Argentina, Chile and Colombia and 9 species in North America, however only 2 species of *Plutella* have been recorded in Europe (Kfir, 1998).

History of *P. xylostella* in Malaysia: *Plutella xylostella* was first recorded in Frasers Hill, Pahang, in 1925 (Ooi, 1986) and by 1941 it had become a major pest in both highland and lowland areas. (Corbett and Pagden, 1941). Since then it has been widely recognized as a serious pest of crucifers. Total losses can reach 70-90% if no control measures are taken (Omar and Mamat, 1997). The history and control of *P. xylostella* in Malaysia is summarized in Table 1.

The pest status of *P. xylostella* was exacerbated in Malaysia, as in many other areas where this pest has spread to, by the lack of endemic natural enemies and the presence of extensive cultivation of crucifers, especially varieties of Chinese cabbage, *Brassica chinensis* var. *pekinensis* in the Cameron Highlands (Ooi, 1986). Farmers reportedly invested 30% of production costs on the control of *P. xylostella* in early 1970s but 70% still failed to achieve satisfactory control (Lim, 1974). By the 1980s, pyrethroids failed to control *P. xylostella* due to high levels of resistance, leading to the increased use of acylurease and *Bt*. By the late 1980s, the acylurease were also failing due to resistance in both lowland and highland Malaysia (Table 1). The lowland populations of *P. xylostella* were found to have higher level of resistance to acylurease, probably due to greater number of generations per year compared with the cooler highlands.

Management of *Plutella xylostella:* In most countries newly introduced pesticides face little registration hurdles, as a result most of which are not registered in the country of origin are readily available at subsidized price. Because of poor enforcement of restrictions on pesticide use, the insecticides registered for rice or cotton are often applied to crucifers which contribute to the overuse and complete dependence on insecticides to control *P. xylostella*. This sole reliance on pesticides for control facilitates the rapid build up of resistance. The failure of insecticides to control *P. xylostella*, interest is growing in cultural controls (Talekar and Shelton 1993), which is one of the oldest methods of pest control and since centuries farmers have been using it, for example change in planting date of rice and wheat to prevent them from rice borer and wheat stem maggot damage respectively. Similarly, the disposal of corn residues was recommended in Europe as early as 1897 in order to reduce overwintering populations of European corn borer (Debach and Rosen, 1991). Dent (1991) defined cultural method as a prophylactic method of control and should be considered as the first ditch defense around which to build other control options.

Some of cultural practices and other control methods for *P. xylostella* are discussed in following sections.

Crop rotation: Since *P. xylostella* has a narrow host range, the local elimination of the host via crop rotation could prove to be

Table 1: Key events in the history of *Plutella xylostella* management in Malaysia

Year	Events
1925	*Plutella xylostella* recorded in Malaysia (Fraser's Hill)
1934	First reported in Cameron Highlands.
1941	Recognized as a major pest of cruciferous vegetables.
1950	Boom of synthetic organic insecticides.
1950-88	Intensive insecticide use (organochlorides, organophosphates, carbamates, pyrethroids, acylurease)
1957	Insecticide resistance (to the organochlorines, DDT and BHC) in *P. xylostella* first reported.
1965	Biology of *P. xylostella* described.
1969	Ineffective insecticides replaced by organophosphates and carbamates.
1972	Resistance to organophosphates reported.
1973	*Cotesia plutellae* Kurd. (Hymenoptera: Braconidae) discovered in Cameron Highlands.
1974	Implementation of IPM suggested; pyrethroids introduced
1975	Biocontrol program initiated.
1975-87	*Cotesia plutellae* fails to achieve more than 35% parasitism
1975	Fungal pathogens discovered (*Zoopthora radicans* and *Tetrastichus ayyari*)
1976	Introduction of exotic parasitoids (*Diadegma semiclausum* Hellén, *Diadromus collaris* Grav. and *Macromalon orientale* Kerr (Hymenoptera: Ichneumonidae)
1977	*Diadegma semiclausum* and *D. collaris* established locally.
1978	Multiple and cross-resistance of *P. xylostella* confirmed.
1982	Public outcry over insecticide residues on cabbages following *P. xylostella* control.
1983	IPM trials and resistance to permethrin and other hard pesticides causes use-shift to acylurease (eg., diflubenzuron, teflubenzuron), *Bacillus thuringiensis* var. kurstaki [*Btk*; Dipel $^{(R)}$] and abamectin [Dynamec©]
1984	Granulosis virus of *P. xylostella* reported. Wide use of acylureas (initially diflubenzuron, then teflubenzuron and chlorfluazuron)
1987	Singapore objects to pesticide residues in Malaysian cabbages and bans imports
1988	Resistance to acylureas causes use-shift to *Bt*. based products; initially *Btk* then also *Bt* var. aizawai [*Bta*; Florbac©]
1988	*Diadegma semiclausum* becomes dominant parasitoid over *Cotesia plutellae.*
1989	*Plutella xylostella* populations reduced *ca.* 8-fold (with greatly reduced insecticide input)
1992	First report of *Btk* resistance.
1992-93	Reports of hard pesticide (eg. organophosphates, pyrethroids) use in Malaysian lowlands.
1994	Reports of sporadic control failures with *Bt*-based products (and abamectin) in the Cameron Highlands (and Malaysian lowlands)
1996	Reports of resistance to *Bta* and abamectin in the field population of *P. xylostella* in the Cameron Highlands.
2001	Report of resistance to *Bt* canola

Sudderddin and Kok (1978), Ooi (1986), Ooi (1992), Loke *et al.* (1992), Furlong *et al.* (1994), Iqbal *et al.* (1996); Sayyed *et al.* (2001)

Table 2: A summary of insecticide resistance in *Plutella xylostella*

Insecticide	Mechanism of Resistance	References
Organophosphates	AchE insensitivity (Ki 20-50 difference); Microsomal oxidation probably not involved.; Glutathione- S-transferase degradation for some Ops Carboxylesterase hydrolysis for Malathion Acetylcholinesterase(AchE) insensitivity Oxidative, Detoxication.	Noppun *et al.* (1986).
Carbamates	Reduced penetration Nerve insensitivity Microsomal oxidation	Sun *et al.* (1978).
Pyrethroids	Microsomal oxidation	Liu *et al.* (1982); Hama (1986); Makino and Horikiri (1985); Noppun *et al.* (1986); Horikiri and Makino (1987)
Acylurease	Reduction in binding to Brush Border membrane of the midgut epithelium; Reduce Activation of toxins; Proteolysis	Rushtapkornchai and Vattantangum (1986); Miyata *et al.* (1988); Fauziah *et al.* (1992).
Bacillus thuringiensis products		Tabashnik *et al.* (1987) Oppert *et al.* (1997); Sayyed *et al.* (2000a,b); Sayyed *et al.* (2001).

a very effective pest and resistance management tactic. A mandatory crucifer-free period has been undertaken for *P. xylostella* control in regions of at least two countries, Mexico and Australia. After the introduction of a summer break in crucifer production in Southern Queensland during 1990, frequency of resistance to the chemical insecticide permethrin appeared to drop sharply (Roush, 2000).

An important part of the long term and sustainable future of production for some crops may be the establishment of grower cooperatives to produce crucifers (and complementary vegetable crops) in alternate times of the year to defeat pests such the *P. xylostella,* while stabilizing crop markets. The growers, who do this will remain highly profitable and retain access to relatively cheap and effective insecticides, whereas growers those can not practice host-free periods will probably eventually suffer an economic decline.

Intercropping: The traditional approach to farming is utilization of poly culture which include mixed intercropping, strip intercropping, relay intercropping and alley intercropping. In intercropping plants act as physical barrier by disrupting the chemical or visual communication between pest insects and their host plants (Sheehan, 1986). It also increases parasitoids and predators reproductive potential due to great temporal and spatial distribution of nector and pollen sources (Risch, 1981).The earliest success of *P. xylostella* control occurred in intercropping of cabbage with tomato which reduce its population in cabbage (Vostrikov, 1915) as the tomato plant contains a volatile compound which acts as a repellent and adversely effect its oviposition (Buranday and Raros, 1975). While Dover (1986) reported the intercropping of brassica with white clover resulting in reduced oviposition by *P. xylostella.* The dill and garlic have also been reported to act as repellent against *P. xylostella* (Talekar *et al.,* 1986).

Trap cropping: The use of trap crop has special importance to subsistence farming in developing countries by reducing reliance on pesticides and lowering production costs (Hokkanen, 1991). The pests often show preference for certain plants is the main principle of trap cropping. Indian mustard has been used successfully as a trap crop for *P. xylostella* control in India (Srinivasan and Moorthy, 1992) however it failed in several other countries like Taiwan, South East Asia and Canada (Talekar, 1996). Similarly, planting collards in field peripheries is a potentially effective trap crop to manage *P. xylostella* in cabbage (Mitchell *et al.*, 2000). Effective trap cropping may eliminate all insecticides as *P. xylostella* is retained in trap crop and become heavily parasitized.

Resistant varieties: Resistant plant material is an attractive alternative or supplement to insecticide control (Eckenrode *et al.*, 1981). The dense and easily abraided microscopic wax crystals or waxblooms on the plant surface can interfere with attachment by insects (Juniper, 1995). On the other hand waxblooms by impairing the mobility and effectiveness of predatory insects can increase herbivore populations. For example, the proportion of time spent walking by three generalist predator species is greater on a *Brassica oleracea* with glossy or reduced-waxbloom mutation than on a normal waxbloom variety (Eigenbrode *et al.*, 1996). As a results these predator species reduce populations of *P. xylostella* on reduced-waxbloom compared with normal waxbloom varieties. Similar results were reported on glossy *B. oleracea P. xylostella* population by using *Chrysoperla plorabunda* and *Hippodamia convergens* (Eigenbrode and Kabalo, 1999). Glossy leaf waxes apparently elicit non-acceptance behaviour in neonate larvae which result in their failure to successfully establish on these plants (Eigenbrode and Shelton, 1990).

Threshold: *Plutella xylostella* has developed resistance to every pesticidal group due to indiscriminate use of pesticides. The frequency of chemical application can be reduced by working out the optimal control thresholds (Chen and Su, 1986). The accepted theory of pest management favoured the application of pesticides when insect pests population approach or exceed on economic threshold which could lead to better and more effective way of pesticide use (Metcalf, 1980). The threshold levels are based upon the larval stage (Kami, 1995). Harcourt (1957) were the first to establish injury equivalencies for lepidopterous pests of cabbage and was expressed as cabbage looper equivalents (CLE) for example the calculated CLE for *P. xylostella* larvae is 0.05 (Harcourt, 1957). Maltais *et al.* (1994) have shown reduced number of sprays with out endangering yield or quality levels of cabbage based on 0.5-1.0 larvae of *P. xylostella* per plant threshold.

Insect sterilization: The sterile insect technique has mainly been used against Diptera (Lindquist, 1986). However, the partial sterility or inherited sterility could be used for the control of lepidopterous pests (Omar and Mamat, 1997). The main principle of releasing sterile male insects into the natural population is that these insects mate normally with females which lay infertile eggs (Smith *et al.*, 1964). In order to induce inherited sterility in many insects the ionizing radiation has been used (Omar and Mamat, 1997). The first coordinated attempt to control the *P. xylostella* in Malaysia was carried out by use of this technique (Ho, 1965). Lepidopterous insects require higher doses of radiation compared with other insects for example Omar and Mamat (1997) reported that a dose between 150 and 200 GY would be suitable for inherited sterility of *P. xylostella*. Similarly Cook and Hooper (1974) measured the sterilizing effects of an alkylating agent or azirdine compound phenyl metepa on adults of *P. xylostella*. Males were sterilized after three hours of exposure without effect on the fecundity of females. However these compounds are not recommended as ideal chemosterilants as these have toxicity to mammals. Therefore, more potential chemosterilants have to be evaluated.

Sex pheromones: Sex pheromone are substances produced by the females to attract male for the purpose of mating. Sex pheromones of lepidopterous insects were introduced as biorational chemicals for pest management in the early 1970s (Chow *et al.*, 1974). The evidences for sex Pheromone emission in female adults of *P. xylostella* was initially reported from Taiwan (Chow *et al.*, 1974). The major component of *P. xylostella* pheromone are (Z)-11-hexadecenal (Z-11_16:Ald), (Z)-11-hexadecenyl acetate (Z-11-16:Ac), (Z)-11-hexadecenyl alcohol (Z-11-16:oh) (Chow and Lin, 1983). The mixture of Z11-16:Ald and Z11-16: Ac in the range 8+ 2 to 4+ 6 has been found to be highly attractive to males in the field (Koshihara *et al.*, 1978), however by adding 1% (Z)-11-hexadecenol (Z-11-16:OH) to the bait could significantly enhance male capture (Koshihara and Yamada, 1981). It was found in later studies that synthetic sex pheromones were effective in attracting same number of adult males as by 10 virgin females (Michereff *et al.*, 2000). Tamaki *et al.* (1977) have reported that *P. xylostella* can effectively be controlled by using synthetic pheromones in conjunctions with reduced insecticidal spray application. Similar results were shown by Reddy and Guerrero (2000 and 2001).

Mating disruption with sex pheromones is an alternative to traditional pesticides for insect control (Ridgeway *et al.*, 1990). It has been found that mating disruption can be used to protect cabbage from *P. xylostella* if pheromones are applied with some supplemental application of insecticides (Mitchell *et al.*, 1997). In contrast, Schroeder *et al.* (2000) reported that mating disruption of *P. xylostella* with the present technology was not effective even under very controlled conditions. The sex pheromones have also been found to increase the contact of *P. xylostella* adults with toxic pathogens (Furlong *et al.*, 1995).

Biological control: Debach and Rosen (1991) defined biological control as the utilization of natural enemies (predators, parasites and pathogens) to reduce the damage caused by noxious organisms to tolerable levels.

Natural enemies can be utilized in three ways:

I) Importation of exotic species and their establishment in a new habitat
ii) Augmentation of established species through direct manipulation of their population.
iii) Conservation through manipulation of the environment.

The history of biological control dates back to 900 and 1200 A.D. when Chinese used predatory ants for control of citrus pests (Debach and Rosen, 1991). Similarly in Arabia, the growers had been using colonies of predatory ants from the mountains to control a pest ant which often destroyed the trees (Sweetman, 1958). However, the first movement of a natural enemy from one country to another occurred in 1762 with the introduction of Mynahbird, *Acridotheres tristis* from India to Mauritius to use against the red Locust, *Nomadacris septemfasciata* Serv. (Sweetman, 1958). The modern day example of deliberate manipulation of insect natural enemies to suppress pest population was the importation of the Vedalia lady beetle *Rodolia cardinalis* Mul. into California in 1888 to control the cotton Cushion Scale, *Icery purchasi* Mask. on citrus (Dent, 1991). This was an immediate success which generated the support for many other biological control projects.

Biological control when applied successfully to pest problem can provide a relatively permanent and economical solution (Huffaker and Messenger, 1976) and is potentially a cheaper compared with chemical control. Greathead (1984) reported that biological control efforts had resulted in economic success in only 1% of cases and the activity of natural enemies is influenced not only by their direct relationship with their hosts but also by their environmental inter-relationship.

Parasitoids: The term parasitoid was introduced in 1913 (Godfray, 1994) and was defined as " the larva feeds exclusively on its host, eventually killing it. It requires a single host to complete development and are intermediate between predators and parasites.

An insect parasitoid can be characterized as follow

1. The development of the parasitoid results in the death of the host.
2. The host is also an insect.
3. The parasitoid is relatively large in relation to the host.
4. The parasitoid is parasitic at larval stages whereas the adults being free living.
5. The parasitoid does not exhibit heteroecism (passing different stages of life history in different hosts)
6. Their action resembles the predators than parasites

The majority of parasitoids are either members of order Hymenoptera or Diptera (Godfray, 1994). There are about 50000 described species of hymenopterous parasitoids (Gaston, 1991), 15000 described species of dipteran parasitoids while about 3000 species in other orders (Eggleton and Belshaw, 1992). There are 8 millions described species of insects (Gaston, 1991) therefore parasitoids constitutes about 8.5% of all prescribed insects.

The first case of parasitism was recorded from cabbage butterfly *Pieris rapae* L. which was attacked by a gregarious internal parasitoid *Apanteles glomeratus* L. and emerged to form a conspicuous cocoon on the integument of its host. *Angitia laterallis* Grav was the first parasitoid recorded on *P. xylostella* by Muggeridge (1930) in Newzealand. By 1979 more than 90 species of *P. xylostella* parasitoids had been catalogued (Goodwin, 1979) and are possible alternative to chemical control (Chua and Ooi, 1986). Historically, indigenous species parasitoids particularly *Diadegma semiclausum* kept *P. xylostella* population below economic threshold levels in USA, Europe and Africa (Biever *et al.*, 1992). Because of this potential for control, *D. semiclasum* and *D. collaris* were introduced to Newzealand from UK (Thomas and Ferguson, 1989). *Diadegma semiclausum* as an introduced parasitoid has controlled *P. xylostella* in certain areas of Malaysia, Taiwan, Philippines, Indonesia, Thailand, Newzealand, Zambia and the Cape Verde Islands (Lim, 1992). In the United States of America *P. xylostella* was held in check by indigenous parasitoids with *D. insulare* Cres. (Harcourt, 1986). Similarly in Australia, population of *P. xylostella* has also been reported to be kept under control by introduced *D. eucerophaga* Hors., *D. rapi.* Cam., *D. collaris*, *Apanteles ippeus*, *Cotesia plutellae* kurdg. (Goodwin, 1979). The introduction of *D. eucerophaga* to Indonesia has led to an average parasitism of over 80% resulting in decline of *P. xylostella* populations subjected to less insecticidal use (Vos, 1953). In Taiwan *C. plutella* was regarded as one of the most promising biological control agents of *P. xylostella* (Chiu and Chien, 1972) but could not give adequate control therefore *D. semiclausum* was introduced from Indonesia, however it failed to establish (Talekar, 1988). While in Trinidad *C. plutellae* and *Tetrostichus sokolowwskii* kurdj. become well established but had not given an effective control of *P. xylostella* (Yaseen, 1974). While in Hawaii *C. plutellae* parasitized up to 95% of *P. xylostella* larvae in the field (Bach and Tabashnik, 1990). In Pakistan *T. sokolowwskii* kurdj. is well established and have been reported to suppress *P. xylostella* populations in various climatic conditions of Pakistan (Mushtaque, 1990). In northern Japan the exotic parasitoid, *D. semiclausum* was introduced and augmented to suppress the density of the *P. xylostella* in cabbage fields and it was found that percentage parasitism by *D. semiclausum* reached only up to 53% in the release field in mid June (Noda *et al.*, 2000). In contrast in the Papua New Guinea highlands release and successful establishment of the *D. semiclausum* reduced crop losses remarkably since 1995 (Saucke *et al.*, 2000).

In the Cameron Highlands of Malaysia, where only one parasitoid *Tetrastichus ayyari* was present but with out adequate suppression of *P. xylostella* (Lim, 1982), three species of parasitoids *D. semiclausum*, *D. collaris* and the larval parasitoid *Macromalon orientale* were introduced from Australia, India, Indonesia and Newzealand during 1975-78 (Ooi, 1986), although only *D. semiclausum* and *D. collaris* become fully established (Lim, 1982). Further studies conducted during 1988-90 revealed that *D. semiclausam* had become the dominant parasitoid with *C . plutellae* becoming less common (Ooi, 1992).The time taken for *D. semiclausum* to become established may be due to the result of excessive use of insecticides in the region since it is observed to be more susceptible to insecticides compared with *C. plutellae* (Furlong *et al.*, 1994).

Laboratory studies indicated a temperature range of 20-30 °C as an optimum for parasitization of *P. xylostella* by *C. plutellae* and 15-25 °C for *D. semiclausum* (Talekar and Yang, 1991). As the temperature approaches 30 °C parasitism by *D. semiclausum* drops sharply (Talekar, 1992). For example in the highland areas of the northern Philippines a single release of *D. semiclausum* resulted in 64% parasitism of *P. xylostella* (Poelking, 1992).

Predators: Predatory species have been used for biological control purpose since ancient time and the use of ants in Asia antedates written records. Predators could be an important mortality factor to *P. xylostella* and cause an average of 90% mortality to first instar larvae (Muckenfuss and Shepard, 1994). While Ullyet (1947) reported that predatory arthropods are an important source of *P. xylostella* mortality and include Stophylinids, Wasps of genus Polistes, Syrphids, Chrysopids, Hemerobiid and Anthocorrids. However, surprisingly little attention has been given in assessing the role of predators in *P. xylostella* management but their destruction by insecticides application could contribute to pest resurgence. The glossy plants could enhance the predation as several predators move with difficulty on normal-wax brassica plants. The glossy plant leaves also reduced the mining of first instar larvae of *P. xylostella* thus expose them to predators (Eigenbrode *et al.*, 1995). For example the predation of *P. xylostella* larvae by *Hippodamia convergens*, *Orius insidiosus* and *Chrysopa cornea* adult females was significantly greater on glossy types as compared with normal-wax or wild-type counterparts however the later was also effective on normal wax plants (Eigenbrode *et al.*, 1995, Eigenbrode and Kabalo, 1999). Similarly ground dwelling spider, *Lycosid spiders* are also major biotic mortality agents of immature stages of *P. xylostella* especially to third and fourth instar larvae (Nemoto, 1993). Among other predators *Micraspis discolor*, *Pardosa pseudoannulata*, *Cheilomenes sexmaculatus* and *Episyrphus alterans* have been observed as controlling agent of *P. xylostella* (Karim, 1995).

Virus: Virus disease of insects was first discovered in 1856 A.D. from diseased silkworm larvae, but a plant disease produced by a virus can be traced back 1555 A.D. (Sweetman, 1958). The best-known insect viruses are the baculoviruses, which contain DNA and are either nuclear polyhedral or granulosis viruses (Entwistle and Evans, 1985). Asayama and Osaki (1970) were the first to observe granulosis virus infecting *P. xylostella* and their potential as control agent for *P. xylostella* has been reported by Nakahara *et al.* (1986) and Su (1990). Abdul Kadir *et al.* (1999) have shown that granulosis virus was highly infective against *P. xylostella* and further suggested that it could be developed as a selective microbial pesticide. The colour of the infected larval body turned to pale green, pale yellow green and to pale yellow in contrast with the dull green of a healthy green. The infected larvae large in size, greater in length and discharged a milky white fluid from its puffy integument (Asayama and Osaki, 1970). The nuclear polyhedrosis virus of Alfalfa looper *Autographa californica* (AcMNPV) and closely related genomic variants such as *Galleria mellonella* (MNPV) are also infective to *P. xylostella* (Farrar and Ridgway, 1999). The nuclear polyhedrosis virus infect the hypodermal tracheal matrix and fat body, whereas the external symptoms are that the larvae become swollen and flucid and the integument become shiny. After death the integument disintegrate and the dead larvae assume the typical melted appearance of larvae with nuclear polyhedrosis.

Entomopathogenic fungi: Fungi is the first microorganism recognized to produce disease among insects (Sweetman, 1958). The infectious nature of fungus disease *Beauveria brassiana* in Silkworms was first reported in 1835. The entomopathogen fungi mainly belong to order Entomophthorales with about 35 genera infecting insects (Burges and Hussey, 1971). Fungi usually infect insects by penetration of the body cavity via the integument and then proliferate, filling the body with hyphae (Steinhaus, 1973). The larvae and some times pupae of the *P. xylostella* has been attacked by several species including *Erynia blunckii* and *Zoophthora radican* (Wilding, 1986). *Zoophthora radicans* periodically causes high mortality in *P. xylostella* population in the countries where it has been recovered. In Newzealand for example, under natural conditions it almost eliminated a population of *P. xylostella* within 10 days, while in South Africa mortality was so high that hymenopterous parasitoids of the *P. xylostella* were eliminated through the absence of their hosts (Ullyet, 1947). The larvae killed by the *E. blunckii* are fixed to the substrate by rhizoids and become covered in a fett-like mate of conidiophores. Roberts (1989) reported that *P. xylostella* is susceptible to different propagules of Beauveria (*B. bassiana* and *B. brongniartii*) and concluded that 6 days after treatment for the experiments to be read is sufficient when the fungal strain is pathogenic to *P. xylostella*. Vandenberg *et al.* (1998) have reported the potential *B. bassiana* to control *P. xylostella* and Shelton *et al.* (1998) have shown that *P. xylostella* larvae appeared to be more susceptible to *B. bassiana* in later instars.

Entomopathogenic nematodes: The number of nematodes species attacking insects is far greater than generally realized. The great majority have not been described yet (Sweetman, 1958). The nematodes which attack the insects are of Nemathelminthes and include in the classes Nematoda and Nematomorpha, however some members of Acanthocephala spend their larval stage in an insect host and the adult stage in mammals (Debach, 1964). The Entomopathogenic nematodes (Steinernematidae and Heterorhabditidae) have been successfully used to control a number of soil dwelling insect pests (Gaugler and Kaya, 1990). However, their requirements for high humidity, moderate temperature and protection from ultraviolet light have severely limited their utility in foliar application (Gaugler and Kaya, 1990). It has been shown that *Steinernema carpocopsae* is the most effective nematode against *P. xylostella* giving 100% mortality after 6 hours of exposure and could cause 40% mortality to immature and mature pupae (Ratnasinghe and Hague, 1998). The foliage application of infective juveniles (IJS) of *S. carpocapsae* against larvae of *P. xylostella* with hydraulic nozzles gave 98% mortality (Lello *et al.*, 1996). While the application of infective juveniles (IJS) of *Steinernema* spp. and *Heterorhabditis indicus* indicated that the infection of *P. xylostella* could start within 3 hours postexposure resulting in significant levels of mortality although maximum infection did not occur until 24 hours of exposure (Mason and Wright, 1997).

Chemical control: Insect control using repelling plants (Smith and Secoy, 1981) or natural products such as sulphur combined with religion, ritual and superstition, began with early civilization and continues through the middle ages to the agricultural revolution (Conacher, 1986). As broad scale agriculture emerged, botanical preparations such as nicotine, pyrethrum, hellebore were used more widely (Ordish, 1967).

The *P. xylostella* feed on highly valued crucifer crops effective control is therefore, necessary, the mainstay of control has been the use of synthetic chemicals. The general use pattern of insecticide vary widely over geographical locations. The most dramatic pattern of insecticide use has been occurred in South East Asia where *P. xylostella* is the major problem of crucifers. For example in Thailand a dominant product like mevinphos provided excellent control in 1965, fair control in 1974 and poor control in 1984 (Rushtapakornchai and Vettabatangum, 1986). Similar pattern have also been observed in Malaysia (Table 1), Taiwan (Sun *et al.*, 1978), Japan (Hama, 1992) and other parts of the world (Tabashnik *et al.*, 1987).

Bacillus thuringiensis (*Bt*): represents the major class of microbes used for insect biocontrol (Macintosh *et al.*, 1991). It is a gram-positive soil bacterium distinguished from other bacilli by its production of parasporal crystal proteins (Yamamoto and Powell, 1993). Cry proteins are produced as crystalline inclusions within the bacterium and must be solubilized and cleaved by protease in the insect midgut to form active toxins. The activated toxins then bind to specific receptor sites on insect midgut brush border membranes, leading to the formation of pores and cell lysis (Schnepf *et al.*, 1998).

Development of resistance in *Plutella xylostella* : *Plutella xylostella* has a long history of becoming resistant to every insecticide (Talekar and Shelton, 1993). Insecticide resistance in *P. xylostella* is particularly widespread in South East Asia because of rapid turnover of insect generations, a long and continuous cropping season, the extensive area of crucifers grown, their high value and frequent insecticides application (Magagro and Edelson, 1990; Sun, 1992).

The first report of insecticide resistance in *P. xylostella* was in 1953 against DDT in Lembang, Indonesia (Ankersmit, 1953). Populations of *P. xylostella* have since been reported to become resistant to most of other classes of insecticides (Table 2).

Since the first commercial *Bt* formulations appeared in the late 1930s, they have been used widely as niche products for pest control (Sayyed, 2000). It has been presumed that resistance to *Bt* toxins was unlikely because of its unique mode of action. However, this was subsequently shown not to be the case and the *Plodia interpunctella* was the first insect reported to have developed resistance to *Bt* toxins albeit under laboratory conditions (Tabashnik, 1994). While various other insect species have been subsequently shown to develop resistance under laboratory conditions, the *P. xylostella* remains the only insect species which has developed resistance in the field (Sayyed *et al.*, 2000a,b). The initial cases of resistance to *Bt* in *P. xylostella* was caused by repeated foliar sprays of *B. thuringiensis* var. *kurstaki* in Philippines and Hawaii (Tabashnik *et al.,* 1990). Resistance has now been reported in Malaysia, Thailand, Japan, Philippines and the USA (Tabashnik, 1994; Imai and Mori, 1999; Liu *et al.*, 2000; Sayyed *et al.*, 2000a; Sayyed and Wright, 2001). The development of resistance to *Bt* toxins is seriously threatening their life expectancy as pest control agents, particularly with the introduction of commercially grown transgenic crops expressing insecticidal *Bt* proteins which increase the risk of resistance by providing a constant selection pressure (Tabashnik *et al.*, 1998; Sayyed *et al.*, 2000a).

Integrated pest management (IPM): *Bacillus thuringiensis* has become a cornerstone to IPM particularly on some vegetable crops (Marrone, 1994).

The broad definition of IPM, adopted by the FAO panel of experts is: " Integrated pest control is a pest management system that in the context of the associated environment and the population dynamics of the pest species utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury level (FAO, 1975). While Kogan (1998) defined IPM as "a decision support system for the selection and use of pest control tactics, single or harmoniously co-ordinated into a management strategy, based on cost/benefit analyses that take into account the interests of an impacts on produce, society and the environment".

The idea of IPM started in the late nineteenth century, when, in the absence of pesticides, crop protection specialists relied on knowledge of pest biology and cultural strategies (Gains, 1957). Interest in IPM declined in the early 1940s with the advent of organochlorine and organophosphate insecticides but by the late 1950s insecticide resistance, resurgence of primary pests, upsurges of secondary pests and overall environmental contamination rekindled interest in more integrated control concepts (Zadoks, 1993). IPM is not a technology package, rather it resembles a "technology basket", intelligent decision have to be made on what techniques in the basket are suitable for a particular location and problem (Teng, 1989). Effective IPM programmes require a holistic and multitactic strategy that enhances the compatibility of pesticides and biological control agents and thus reduces the number and rate of pesticide applications (Sayyed and Arif, 2000). The possibility of integrating microbial agents such as *Bt* with other biological control agents, culture practices and conventional pesticides has increased considerably with the availability of *Bt* strains and toxins with broader host ranges, improved formulations and more varied options for their application, including transgenic crops. *Bacillus thuringiensis* products are far more specific than traditional insecticides and have few direct toxic effects upon specialist and generalist natural enemies (Losey *et al.*, 1999). For example, Cry1Ac expressed in cotton did not produce a toxic effect on several beneficial insects, such as green lacewing, *Chrysoperla carnea* Steph (Lozzia *et al.*, 1998). The use of NewLeaf®potato containing Cry3A was shown to enhance the population of predators in fields that were protected from the Colorado potato beetle damage without the need for conventional insecticide applications (Feldman and Stone, 1997). Similarly, use of *Bt* cotton in China resulted in an average increase of 24% in the number of insect predators over what was found in conventional cotton field (Xia *et al.*, 1999).

In Asia, there has been interest in IPM since the late 1970s (Lim, 1990). Planting of trap crops is one of the cultural methods used for pest management of *P. xylostella* (Metcalf and Luckman, 1994). For example, in India the mustard, *Brassica junciais* is used to attract *P. xylostella*, thus reducing the need for insecticides to a maximum of two sprays compared with 10 or more per season using conventional control methods (Srinivasan and Moorthy, 1992). While in Japan, yellow sticky traps to capture *P. xylostella* adults plus three sprays of *Bt* were shown to achieve better control than five sprays of *Bt* (Rushtapakornchai *et al.*, 1992). In Taiwan, the introduction of two larval parasitoids, pheromone traps and *Bt* sprays reduced the *P. xylostella* population density on cauliflower and broccoli to a lower level as compared with neighboring, conventionally sprayed plots (Talekar, 1996). Similarly, Chilcutt and Tabashnik (1999) reported that a combination of parasitoids and *Bt* generally gave better control of *P. xylostella* over time than either alone. Ivey and Johnson (1998) reported the greatest yield and value of marketable cabbage when a resistant variety and *Bt* were incorporated together in an IPM system.

Conclusion: In the last four decades, *P. xylostella* has become most difficult pest to control because of its intrinsic biology and ecology . The main cause of the failure is the development of resistance by *P. xylostella* to every group of insecticides used including *Bt.* However, parasitoids *D. semiclausum* and *C. plutellae* have been controlling this pest successfully in highlands and lowlands respectively in South East Asia, which provide the basic model for IPM and use of *Bt* with these parasitoids could be a success against *P. xylostella* as *Bt* has no or minimal effect on beneficial insects (Losey *et al.*, 1999).

The development of insect-resistant *Bt* crops has been of major significance in the control of insect pests on cotton, maize, potato, rice and a variety of other crops (Hilder and Boulter, 1999). The use of *Bt* crops have proven successful in several parts of the world because of higher yields and fewer insecticide treatments for target pests (Klotz-Ingram *et al.*, 1999). In a recent study it has been shown that the rapid adoption of this technology is directly tied to benefits of greater effectiveness in pest control technology and very competitive cuts in farmer's costs (Gianessi and Carpenter, 1999; Betz *et al.*, 2000). However, field use of *Bt*-based spray products has highlighted the problem of evolution of *Bt* resistant populations of insect pests. In recent reports *P. xylostella* have also been shown to evolve resistance to *Bt* crops in the laboratory (Zhao *et al.*, 2000; Sayyed *et al.*, 2001). In Pakistan these crops are at experimental stage therefore a detailed study is required in local ecosystem in order to have their long term role in integrated pest management, before commercializing them.

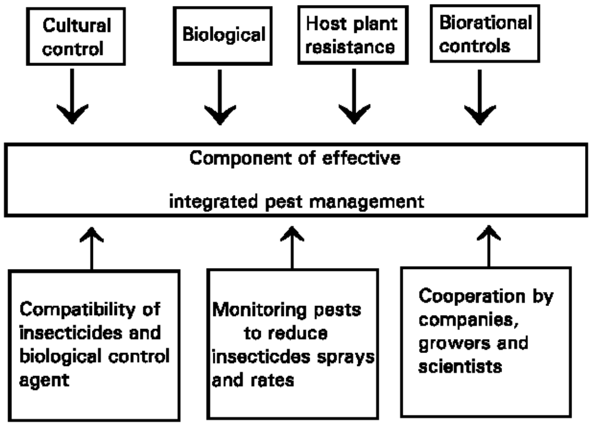

Fig. 1: Effect of integrated pest management programs will incorporate multiple tactics. Pesticides should be used only when needed, at the lowest rates possible and in a manner to reduce negative impacts on natural enemies

Previous experiences with *P. xylostella* management have shown that a single component strategies will fail. Therefore the best solution can be obtained by the use of fully integrated IPM programme, for example host plant resistance, development of new pathogens and insecticides must be available to complement the traditional strategies of biological and cultural control methods (Fig. 1).

There is a need to maintain a source of pesticides because they are powerful and effective pest management tools. However, they should be highly selective, rapid in their impact, adaptable to many situations, relatively economical and compatible to natural enemies. Enhancing the compatibility of pesticides and natural enemies is complex but can reward us with handsome dividends in improved pest control (Metcalf, 1994) and pesticide resistance management (Tabashnik and Croft, 1985).

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