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Review Article

Plant Secondary Metabolites in the Sustainable Diamondback Moth (*Plutella xylostella* l.) Management

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ABSTRACT
Diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) is one of the most important insect pests causing severe damage to crucifers worldwide. Chemical methods have failed to control this pest as this has developed resistance to almost all synthetic insecticides available. Hence, alternative sources such as plants can serve as the rich source of secondary bioactive molecules with insecticidal properties. For the past two decades, considerable efforts have been directed toward screening plants to determine their biological activity against DBM. Additionally, local abundant plant sources can be easily utilised to prepare pesticidal formulations from the local flora. The strategy to maximise control by insecticides from plant origin and reduce selection pressure by applying insecticides only when necessary, and by rotating insecticide use between chemical groups judiciously. The growth inhibiting activity of a phytochemical may be essential for sustainable pest management strategies. While the design of novel crop protection chemicals possessing superior properties is of prime importance. These plant sources can be structurally modified to design new safer insecticidal molecules with novel mode of action for sustainable pest management in future by using modern technologies.

Key Words: Diamondback moth, *Plutella xylostella*, Plant sources, Pest management, Plant extracts

INTRODUCTION

The diamondback moth (DBM), *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), is one of the most destructive insect pests of crucifers worldwide. Larvae of *P. xylostella*, feed on the foliage of the cruciferous plants from the seedling stage to harvest, and greatly reduce the yield and quality of produce. *P. xylostella* has only become a significant pest, with major problems observed in the 1970s apparently caused by the evolution of insecticide resistance (Talekar and Shelton, 2003; Shelton *et al*. 2000). It is an oligophagous species feeds on plants of Brassicaceae, which include economically important crops such as cabbage, cauliflower, broccoli, canola and Brussels sprouts family (Thorsteinson, 1953). It was estimated that the worldwide annual DBM management costs US$ 1 billion (Talekar and Shelton, 1993). Pesticides have dominated *P. xylostella* control programme till date (Syed, 1992; Syed *et al*., 2003; Shelton *et al*., 1993). It has shown significant resistance to almost every insecticide applied in field including biopesticides such as crystal toxins from *B. thuringiensis* and spinosyns from *Saccharopolyspora spinosa* under field conditions (Tabashnik *et al*., 2003; Sarfraz and Keddie, 2005). Insecticide resistance associated crop failure has been reported in Australia South-East Asia, Japan, USA and Central America (Sun, 1992; Endersby and Ridland, 1994). A large number of insecticides with different modes of action are available for the control of susceptible *P. xylostella* but resistance has been observed to all and even to the newest modes of action in one or more regions. Most effort has been devoted to find alternative control measures for this pest because of the negative impact of pesticides and the problems encountered in controlling diamondback moth populations. Botanical insecticides can influence the behaviour and development of the herbivorous insect, which uses the plant for their reproduction. Also, alternative sources of potentially suitable insecticides include botanical insecticides, antifeedants and insect growth regulators of their natural origin having non-neurotoxic modes of action, and low environmental persistence (Arnason *et al*., 1992; Isman, 1994; Isman, 2006). Neem is among few natural products that has gained wide acceptance in some countries. Before the advent of synthetic chemicals, people controlled and killed agricultural and domestic insect pests by physically removing them or by using plant parts and plant derivatives. These plants containing insecticidal phytochemicals were predominantly the secondary metabolites produced to protect themselves against herbivorous insects. However, there is a little other than anecdotal, traditional, or cultural evidence on this topic (Grodner, 1997; Casida and Quistad, 1998). Pyrethrum, derris, quassia, nicotine, hellebore, anabasine, azadirachtin, d-limonene camphor and turpentine were some of the more important phytochemical insecticides widely used in developed countries before the introduction of synthetic organic insecticides (Wood, 2003).

In the past, a number of chemical compounds have been studied for pesticidal activity with a goal of obtaining a product with selectivity to invertebrates such as insects and arachnids, which has little or no toxicity to non-target vertebrate species and does not persist. Most of the products have pesticidal activity of commercial significance at the same time to mammals, fish, fowl or other non-target species e.g. organophosphorus compounds and carbamates inhibit the activity of acetylcholinesterase in insects as well as in all classes of animals. However, in spite of widespread concern about the long-term impact of synthetic pesticides on health and environment particularly in the developed world, natural pesticides have yet to make any major roads to market. In others words, for over three decades, the insecticide market has been dominated by organophosphates, carbamates and synthetic pyrethroids, while only 1% of the global insecticide market is occupied by the two bio-insecticides (*Bt* based products) and insecticides of plant origin (pyrethrum and neem based products) (Isman, 2000). Toxicity and development of resistance issues have limited the use of these synthetic insecticides. Therefore, it is desirable to develop alternative methods for pest management based on biological pesticides, which are safe to both humans and environment (Sakomoto *et al*., 2003).

Keeping in view the importance, over a period of 25 years five international workshops have been aimed exclusively on diamondback moth management. Numerous researchers published abundant information in the form of research articles on the DBM. However, little has been published related to botanicals on their biochemical and physiological effects. Figure 1 shows the number of article published in last 25 years. In this article, we review the current state of knowledge on insecticidal plant sources evaluated against *P. xylostella*, their impact on natural enemies, resistance management, mode of action and future strategies for the sustainable management of *Plutella xylostella*.

Insecticidal activity of secondary metabolites against P. xylostella

The new botanical insecticides have several ecological advantages related to their inherent nature compared to the organically synthesized insecticides. These compounds thus strategically represent the actual concerns in regard to biodiversity and absence of toxic residues. The plant kingdom is the most efficient producer of chemical compounds (primary and secondary metabolites) synthesizing many products having wide array of functions that are used in defence against herbivores (Croteau *et al*., 2000). Primary compounds (*viz.* amino acids, simple sugars, nucleic acids, lipids) are required for basic cellular process, while secondary metabolites include compounds produced in response to stress (Keeling and Bohlman, 2006). Plant secondary metabolites have been exploited by humans for their benefit (Balandrin *et al*., 1985). Plant metabolites are grouped in three broad categories i.e. terpenes and terpenoids (~25000 types), alkaloids (~12000 types) and phenolics (~8000 types) (Croteau *et al*., 2000). Mixture of these compounds may be deterrent to insects for longer period than single compound. Both monoterpenes (C_{10}) and diterpene acids (C_{20}) are toxic to insects and deterrent to herbivores. The secondary metabolites and their constituents have received considerable attention in the search for new molecules having insecticidal activity, repellence, feeding deterrence, reproduction retardation, insect growth regulation against various insect species etc. (Rice and Coats, 1994; Isman, 2000). Toxicity has also been reported against nematodes, mites and other agricultural pests, and antifungal, antiviral and antibacterial properties against pathogens (Prakash and Rao, 1986; 1997; Copping and Menn, 2000). The secondary metabolites may not cause instant mortality, but their effects are manifested by an adverse impact on normal biochemical and physiological functions (Prakash and Rao, 1997). Several studies disclose the use of naturally occurring substances as mostly referring to single species of insect or for a natural product having many components. During the last two decades, considerable efforts have been directed toward screening plants for their biological activity against insects. Morallo-Rejesus (1986) published a review on "botanical insecticides against the diamondback moth", which included the plants possessing insecticidal activity against DBM. He added six plant species *viz. Aristolochia elegans, A. tagala, Ageratum conyzoides, Blumea balsamifera, Caesalpinia pulcherrima, Derris philippinensis* to the existing 82 species reported by Grainge *et al.* (1984) that possess insecticidal properties against diamondback moth in the Philippines. Extract of these plants exhibited one, or a combination of two or more effects i.e. toxic, antifeedant, repellent, sterillent, growth inhibiting etc. Majority of the insecticidal plant species reported belongs to plant families Asteraceae, Fabaceae and Euphorbiaceae e.g. pyrethrum and rotenone. Many plants from Meliaceae family have been screened due to the outstanding bioactivity of azadirachtin (limonoid from the neem, *Azadirachta indica*), which are both a potent antifeedant and an insect growth regulator (Schmutterer, 1990; 1992). Furthermore, various laboratory and field experiments were conducted to evaluate plant biological activity against cabbage pests (Hough-Goldstein and Hahn, 1992; Foon and Tong, 1993; Prijono and Hassan, 1993; Hermawan *et al*., 1994; Qiu *et al*., 1998). Numerous plant extracts or plant-derived compounds can potentially be incorporated into an alternative and novel strategy to control *P. xylostella*. Plant chemicals are selective and biodegradable, which suggest environmental acceptability and compatibility in integrated pest management (IPM) programs as well as being effective in resistance management. Some reports have indicated that neem seed extracts are more effective than some synthetic insecticides based on field trials against DBM larvae (Fagoonee, 1987; Dreyer, 1987; Isman, 2000). In developing world, majority of farmers have limited resources to buy and apply chemical pesticides. Thus enforcing the need to exploit the traditional available local plant resources, which are free to the farmer and, therefore, suitable for low-input integrated pest management systems. Extracts, essential oils from plants and their constituents has been shown to be a potent source of botanical pesticides (Guenther, 1948; Shaaya *et al*., 1997; Isman, *et al*., 1991; Schmutterer, 1995; Isman, 2000; Suliman *et al*., 2003). The bioactivity of phytochemicals against DBM larvae can vary significantly depending on the plant species, plant part, solvent used in extraction etc. (Table 1). A large number of studies have been carried on the basis of the traditional knowledge and scientific information on herbs and medicinal plants showing biological activity (insecticidal) against various insect pests including DBM.

Attractant and repellent action of phytochemicals: Attractants and repellents can modify the behavioural response in insects where a given species is either attracted to a bait, or pheromone; or repelled from a host plant by a repulsive agent (Fagoonee, 1987). Any factor that selectively influences the production of either deterrent or stimulant could directly influence the direction in which the balance is tipped. Eighty-eight plant species were reported to be insecticidal to *P. xylostella* and many of these also have repellent properties (Morallo-Rejesus, 1986). Results indicated that syringa and neem extracts might play a role in altering the attractive properties of crucifer plants to *P. xylostella*. Hot pepper has been found to be an effective pesticide indicated repellent action (Gaby, 1988). The pesticidal properties of chilli powder has successfully been used to control DBM on cabbage and lettuce. DBM gravid females showed discrimination in choice to oviposit, female accepts leaves of few closely related species as food (Thorsteinson, 1953). Glucosinolates (present in brassica plants) provides chemical defence against generalist herbivory (Fahey *et al.*, 2001), however, specialists such as *P. xylostella* and *Pieris* spp. (Lepidoptera: Pieridae) use these glucosinolates as feeding and oviposition stimulants (Siemens and Mitchell-Olds, 1996; Fahey *et al.*, 2001; van Loon *et al.*, 2002). Application of botanical insecticides on brassicas have been known to alter the feeding and oviposition preferences of these specialists (Dover, 1985; Javer *et al.*, 1987; Schoonhoven and Luo, 1994). DBM moths are attracted to its brassicaceous host plants by chemical (olfactory/gustatory) and/or physical (tactile/visual) stimuli associated with host plant acceptance and oviposition (Justus and Mitchell, 1996; Badenes-Perez *et al.*, 2004; Shelton, 2004; Bukovinszky *et al.*, 2005).

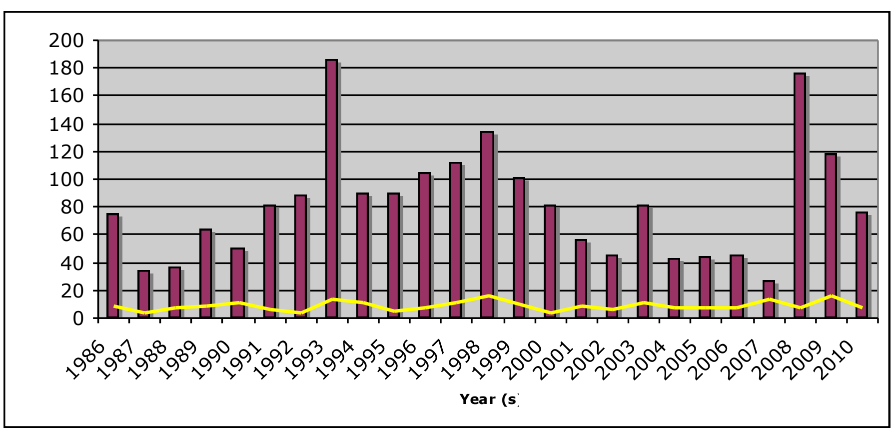

Figure 1: Number of articles published on management of Diamondback moth and insecticide of plant origin (1986-2010). Total number of articles published on *Plutella xylostella* (red), number of articles published on botanical used/tested against *Plutella xylostella* (yellow).

Table 1: Plant species showing different activities against *P. xylostella*

S.No	Activity	Plant species	Plant part	Extraction medium	Reference (s)
1.	Antifeedant and growth regulation	*Afromomum melegueta, A. citratum*	Plant and seed	Methanol and water	Ntonifor *et al*. (2010)
		Ajuga nipponensis	Stem	Chloroform	Shin and Yu (1993); Qiu *et al*. (1994); Huang *et al*. (2008)
		Andrographis paniculata	Stem	Acetone	Hermawan *et al*. (1994)
		Artemisia annua		Alcohol	Peng (2004)
		Artemesia santonicum		Ethanol	Erturk *et al*. (2004)
		Azadiracta indica	Leaves	Water	Charleston *et al.* (2005)
		Curcuma longa	Rhizome	Petroleum ether, chloroform	Morallo-Rejesus *et al*. (1992)
		Euphorbia antiquorum, Euphorbia nivulia, Euphorbia pulcherrima, Euphorbia tirucalli	Leaf	Petroleum ether and ethyl alcohol	Uma *et al.* (2009)
		Melia azedarach	Seed	Alcohol	Sharma *et al*. (2006)
		Rhododendron molle	Flower	Dichloromethane	Shin and Yu (1993)
		Severinia buxifolia	Root (bark)	Chloroform	Wu *et al*. (1997)
2	Fumigant	*Sabina vulgaris*	Seed		Gao and Zhang (1997)
3	Larvicidal	*Annona squamosa*	Seed	Ethanol	Sinchaisri *et al*. (1991), Leatemia and Isman (2004)
		Cyperus rotundus	Roots	Ethanol	Visetson *et al*. (2001)
		Gymnema sylvestre, Solanum khasianum			Seenivasan *et al*. (2003)
4	Insecticides	*Actinidia chinensis*	Stems and leaves	Acetone and petroleum ether	Junshan *et al*. (2008)
		Aglaia roxburghiana	Stem bark	Dichloromethane and methanol	Molleyres *et al*. (1999)
		Alpinia galanga	Rhizomes	Dichloromethane	Dadang *et al*. (1998)
		Cyperus rotundus	Roots (tuber)	Ethanol	Dadang *et al*.(1996)
		Linum bienne, Laurus nobilis, Prunus laurocerasus, Redesaa alba, Scorzonera tomentosa, Scorzonera mollis, Tamarix smyrnensis	Stem	Ethanol	Erturk *et al*. (2004)
		Stellera chamaejasme	Roots	-	Zhang (2000)
		Stemona collinsae	Roots	Dichloromethane	Sinchaisri *et al*. (1991), Phattharaphan *et al*. (2010)
		Zanthoxylum bungeanum, Eucalyptus tereticornis, Nicotiana tabacum, Broussonetia papyrifera,	Leaves and stem	Ethanol	Wei *et al*. (2005)

		Bauhinia variegata, *Duranta repens*, *Euphorbia hirta* and *Camellia oleifera*			
		Melia azedarach, *Laurus nobillis*, *Cissampelos* aff. *glaberrima* and *Croton sp.*	Leaves	Water	Torres and Oliveira (2001)
		Tripterygium wilfordii	Roots (bark)		Xu *et al*. (2006)
5	Ovicidal	*Melia azedarach*	Leaves	Water	Charleston *et al*. (2005)

Growth and reproduction inhibiting phytochemicals: Phytochemicals with a considerable capacity to reduce adult emergence at low dosage, which reduce the recruitment over time is the desired characteristic of botanical insecticides. The adult emergence is affected by phytochemicals, which often cause acute and chronic toxicity. These compounds exhibit effects on developmental stages of exposed larvae, which can produce morphological abnormalities in different developmental stages such as lack of melanization in larval and pupal stages, dead larvae-pupal intermediate stage with the head of pupa and the abdomen of a larva, dead adults with folded wings in pupal exuvium and emerged adults unable to escape the pupal exoskeleton, half ecdysed adults etc. (Facknath and Kawol, 1996). The inhibition of metamorphosis as a result of azadiractin application affected the emergence of pupae due to hormonal disturbance control and/or interference in chitin synthesis during the moulting process (Aldhous, 1992; Mordue and Blackwell, 1993). Antifeedant effects have been observed in the pupae of leaf minor; *Liromyria trifolia* and fruit fly; *Ceratitis capitata* treated with azadiractin (Stark *et al*., 1992). The tetranotriterpenoid (also called limonoid) natural products of Meliaceae, Rutaceae and compound of azadirachtin is responsible for the majority of biological effects observed in organisms exposed to neem compounds i.e. insect antifeedant and growth regulator, antifungal, bactericidal, antiviral and medicinal effects on animals and humans (Isman, 2008; Champagne *et al*., 1992; (Chandramohan and Nanjan, 1992; Mordue and Blackwell, 1993; Verkerk and Wright, 1996;). Exposure of larvae to botanical pesticides appeared to prevent moulting of insects and many died before they could pupate, shows physiological effects with larvae failing to initiate the larval pupal moult (Schmutterer, 1995). Larvae are more susceptible, however, larvae complete their developmental stages but fail to pupate (Kaul and Isman, 1991; Jagannadh and Nair, 1992). Slower rate of development and failure to moult has been reported with neem extracts against *P. xylostella* (Schmutterer, 1995; Isman, 1994). Extended life cycles and lower weight gain rates due to Meliaceae plant extract were also reported (Charleston *et al*., 2005).

The spread of insect pests is strongly influenced by the female's choice of plant parts for oviposition and other oviposition characteristics. Therefore, oviposition deterrence may be of importance to insect pest management by protecting plants from insects before any feeding damage occurs. However, if females still continue to oviposit on low quality plants will result in reduced feeding by larval stages, which also has positive implications for pest management programmes. Völlinger (1987) observed that if *P. xylostella* larvae were fed on cabbage treated with neem formulation resulted in substantial reduction in female fecundity. Olfactometer tests showed that volatiles of chrysanthemum (*Chrysanthemum morifolium*) extract treated host plants were less attractive to *P. xylostella* females and laid only a small proportion of eggs on chrysanthemum extract treated host plants, while ovipositing parasitoid females parasitized a much higher proportion of host larvae feeding on the treated host plants than on untreated host plants (Liu *et al.*, 2006). A number of plant extracts have been shown to reduce oviposition by *P. xylostella* e.g. aqueous extract from neem (Loke *et al*., 1992), tansy; *Tanacetum vulgare* L. (Hough-Goldstein and Hahn, 1992), alcoholic extract of hyssop, rosemerry, sage, thyme and white clover as well as essential oils from sage and thyme (Dover, 1985), *Acorus calamus* and *Vitex negundo* (Murthy *et al.*, 2005). *Azadirachta indica* (0.5%) recorded maximum reduction in oviposition both under no-choice (50.33%) and free choice (62.43%) conditions at 24 hour (Patil and Goud, 2002; 2003). Essential oil of dragon juniper (*Juniperus chinensis* var. *kaizuca*) showed fumigant toxicity activity against the DBM at concentrations 5.00 and 2.50 mg/litre with larval mortality values of 92.33 and 80.29% after 48 hours of fumigation, respectively (Zhao and Hou, 2006). Triterpenoids and tetraterpenoids are the main active ingredients found in these plants (Schmutterer, 1995). Tetranortriterpenoid (toosendanin) isolated from *Melia toosendan* (Meliaceae) showed strong antifeedant, toxic and oviposition inhibitory effects on a range of insects (Chiu, 1985). The impairment of gonotrophic cycle of adults prevented the eggs from hatching (Dilawari *et al*., 1994). Botanical with Insect Growth Regulators (IGRs) have shown pronounced effects on the development period, growth, adult emergence effect, fecundity, fertility and egg hatching resulting in effective control (Shaalan *et al*., 2005). Various plants have been found to contain phytoecdysones, phytojuvenoids and anti juvenile hormones, which acts as IGRs (Verma and Dubey, 1999). However, the progress is slow and no promising botanical IGRs have been commercialized to replace current synthetic IGRs such as methoprene.

Antifeedant Activity: Plant defensive chemicals discourage insect herbivory in natural conditions either by deterring feeding or oviposition (Isman, 2006; Champagne *et al*., 1992). Simple crude extracts from plants have been used as insecticides in many countries for centuries (Crosby, 1971). Extracts from *A. azadiractina* and *Melia azedarach* have demonstrated lethal, sublethal (developmental/growth disrupting) and deterrent (feeding and/or ovipositional) effects against a variety of insect pests including *P. xylostella* (Schmutterer, 1990; Ascher, 1993; Mordue and Blackwell, 1993; Sandhu, 1996; Schmidt *et al*., 1997; Kaur and Singh, 2003). Reduced feeding has been reported in *P. xylostella* treated with different neem preparations exposed to cabbage (Perera *et al*., 2000), and on Chinese kale treated with fruit extract from syringa (Chen *et al*., 1996). Both primary and secondary antifeedant effects of azadirachtin have been observed (Ascher, 1993). Antifeedant activities of secondary metabolites from *Ajuga nipponensis*, *Annona squamosa*, *Lantana camera*, *Euphorbia hirta*, *Melia azedarach* and *Azadiractina indica* have been observed against *P. xylostella* in laboratory bioassay (Leatemia and Isman, 2004 a,b; Charleston *et al*., 2005; Dong *et al*., 2005; Wei *et al*., 2005; Huang, 2008).

Antifeedant compounds belongs to all major classes of secondary metabolites i.e. alkaloids, phenolics and terpenoids (Frazier, 1986). The complex tetranortriterpenoids found within plants from the Meliaceae family are thought to be feeding deterrents (Jacobson, 1989). Griffiths *et al*. (1991) investigated the joint effects of an antifeedant leaf extract of *Ajuga* spp. and the insect growth regulator teflubenzuron on the larvae of DBM feeding on mustard plants. The antifeedant suppressed the feeding and larvae died after 2 weeks. Foliar consumption was reduced by at least 50% and pest mortality was greater than 75% in both the treatments, when applied in combination. Deterrent chemicals play an important, if not major role, in host plant selection by phytophagous insects (Morgan, 1981). Usually some secondary compounds show no bioactivities or attractiveness to insects. Primary effects of azadiractin include the process of chemoreception by the organism (e.g. stimulation of sensory organs on mouthparts), whereas secondary effects are gut motility disorders due to topical application only (Schmutterer, 1990; Ascher, 1993). In terms of secondary plant chemistry, the Meliaceae is characterised by the production of limonoids (a group of modified triterpenes) e.g. neem tree contains around 100 different limonoids in its different tissues (Isman, 2006; Kaul and Isman, 1991). Inhibition of feeding behaviour by azadirachtin results from blockage of input receptors for phagostimulants or by the stimulation of deterrent receptor cells or both (Mordue and Blackwell, 1993). There is need to identify putative deterrent substances that could be isolated in sufficient quantities or synthesized for use as crop protectants.

Impact on natural enemies

Botanical pesticides have been shown to have little impact on natural enemies and therefore can be used in combination with biological control in the development of an integrated pest management system (Schmutterer, 1997). Most of the studies related to investigations of impact of botanical pesticides on natural enemies of *P. xylostella* have been focused on neem. Verkerk and Wright (1993) found that low (sub lethal) doses of neem extracts enhanced parasitism by *Diadegma semiclausum* in the laboratory, and suggested that the increased parasitism was due to stress induced impairment of *P. xylostella* immune system. In another study, it was explained that the development of DBM is significantly prolonged on plant treated with botanical extracts, hence available to natural enemies parasitism for longer period (Charleston *et al*., 2005). Longevity and foraging behaviour of *Diadegma moppila* have no affect when exposed to neem (Akol *et al*., 2002) and also showed no effect on fecundity and activity of female Diadegma semiclausum emerging from *P. xylostella* (Schneider and Madel, 1991; Schmutterer, 1997). These formulations did not effect *C. plutellae* cocoon formation, but found detrimental to the adult emergence (Perera *et al.*, 2000). Syringa and neem extracts have no direct negative influence on *C. plutellae* and *D. collaris* (Gaby, 1988). *C. plutellae* is significantly more attracted to cabbage plants treated with syringa extract than to control plants as showed in wind tunnel experiment (Charleston *et al*., 2005). Also, *Diadegma mopilla* was able to detect and respond differently to volatiles from plants treated with neem and syringa formulations (Akol *et al*., 2003). Similarly, *Cotesia vestalis* adults were attracted to broccoli plants sprayed with yeheb (*Cordeauxia edulis*) methanol leaf extract (Egigu *et al*., 2010).

Insecticide resistance

Majority of the existing synthetic insecticides are known to cause insecticide resistance to one or another insect pest species. Farmers often use large quantity of synthetic insecticides and spray cocktails of chemicals to control these herbivorous insects. In the tropical climate, heavy usage of synthetic insecticides coupled with rapid turnover of DBM generations has lead to development of resistance to practically all classes of synthetic insecticides (Barroga and Morollo-Rejesus, 1981; Sudderuddin and Kok, 1978; Sun *et al*., 1978; Liu *et al*., 1981; Georghiou, 1981; Miyata *et al*., 1982; Miyata *et al*., 1986; Sun *et al*., 1986; Tabashnik *et al*., 1987; Saito *et al*., 1995). *P. xylostella* was the first crop pest to be resistance against DDT (Ankersmit, 1953), and first field to show population resistant to *Bacillus thuringiensis* (Tabashnik *et al*., 1990; Ferré and van Rie, 2002). Natural products are not immune to herbivores resistance, however, delays the resistance build up due to presence of mixture of compounds (Völlinger, 1987). The selection pressure of insecticides to DBM should be reduced by the rational and rotational use of insecticides to retard or avoid the development of insecticide resistance. Insecticide resistance occurs mostly in high temperatures, long growing seasons, multiple insect generations, intense insect pressure, and frequent insecticide applications (Yamada and Koshihara, 1978; Sun *et al*., 1978). Nirmal and Singh (2001) reported the development of resistance to cypermethrin (198-615 fold) and fenvalerate (590-4576 fold). High levels of resistance to the major categories of insecticides, *i.e*., organophaosphorus, carbamates, pyrethroids and DDT, have been detected in the DBM in Taiwan (Sun *et al*., 1986; Talekar and Shelton, 1993) and Malaysia (Syed *et al*., 1992). Resistance to newer insecticide chemistries, including spinosad, indoxacarb and emamectin benzoate, has also been reported (Zhao *et al*., 2006). Variability in the insecticidal effects of botanical preparations has been another major obstacles in insect pest management leading to vulnerabilities such as resistance e.g. commercial neem formulation (Neemix® 4.5) showed varied effect on the development and survival of larvae of the DBM in two different lots (Xian and Sheng, 2005). Indeed, the existence of neem insecticide is attributed to presence of multiple constituents and complex physiological effects (Schmutterer, 1988; Völlinger, 1987). The growth inhibiting properties of phytochemicals may be essential for biorational application leading to new strategies and insect resistance management.

Mode of action

Since, plant produces a variety of secondary compounds, which causes unknown interactions inside the cell caused by enzyme, channel and membrane target assays as supplements for determination of insecticidal activity (Casida and Quistad, 1998). The mode of action and site of effect for larvicidal activities have been studied by various authors (Lewis *et al*., 1993; Zafra-Polo, 1996). The understanding of mode of action of botanicals can lead to a novel compounds with novel properties, which can be achieved with the help of desired structural changes and suitable agricultural use. It has been observed that botanical insecticides affect insect physiology in many different ways (Senthil-Nathan *et al*., 2004). In the laboratory studies, about 80 plant species have been reported to be effective against the DBM either by direct effects on the growth or development or reduced feeding by acting on receptors. Hence, inducing repetitive discharge in the nerve (Gershenzon and Dudareva, 2007). Recently, insecticidal properties of secondary metabolites and their mode of action have been reviewed in detail (Rattan, 2010). Different secondary metabolites have been known for remarkable toxicity targeting the vital biological systems in insects such as neurotoxicity of several monoterpenoids (Coats *et al*., 1991), acetylcholinesterase inhibition (Ryan and Byrne, 1988), blocking octopamine (Enan, 2001), inhibitors of complex I (NADH) (Ahammadsahib *et al*., 1993; Lewis *et al*., 1993; Londershausen *et al*., 1991; Zafra-Polo *et al*., 1996), inhibition of feeding behavior (Mordue and Blackwell, 1993), nicotine acetylecholine receptor (Richards and Cutkomp, 1945; Miyazawa *et al*., 1997), voltage dependent sodium channels etc. (Ohta, 1973; Ohta and Gellespie, 1996; Levi *et al*., 1980; Bloomquist, 1996). Indeed, the poisoning symptom appears in sequence of inactivity, locomotive instability, knockdown, paralysis and slow death. Mechanism action of secondary metabolites along with baseline toxicological information will strengthen the development of commercial plant based insecticidal products with target specificity.

Future: safer chemicals for sustainable pest management

In many part of the world's crucifer producing regions

P. xylostella has developed resistance to every insecticide available. Therefore, more target specific and biodegradable compounds are required to meet the present and future needs (Alkofahi *et al*., 1989). Alternative sources of potentially suitable botanical insecticides having non-neurotoxic modes of action with low environmental persistence are required for future (Arnanson *et al*., 1992; Isman, 1994; Isman, 2006). They may play an important role in the management of *P. xylostella*. Also, resistance to *B. thuringiensis* is complex and *P. xylostella* might develop 70-100 folds resistance to *Bt* toxin as observed in laboratory studies (Tabashnik *et al*., 2003; 1990). Due to pest resurgence problems and impact of non-target organisms associated with the use of toxic synthetic pesticides, there is need to develop safer pesticides with broad range of activities. Considering the climate change perspectives, the pest may have altered seasons and shorter generations cycles, there will be demand for easily available and low cost biodegradable pesticides (Ntonifor, 2011). Identification of novel effective insecticidal compounds from natural plants is essential to combat increasing resistance rates, concern for the environment, food safety and food security. Many researchers are taking up botanicals containing active phytochemicals in their efforts to address some of these problems. Hence, there is need to understand the biochemical mechanisms involved in insect, which can further be used to increase the toxicity and safety to humans and environment.

Inconsistent insecticidal effects of botanical preparations have been the major obstacles. However, understanding of the reason for variability may help to improve preparations of the formulations and develop more practical strategies for field applications. One of the fact may be that the plant species do not always have an identical chemical composition; hence, production can be directed or blocked at one of the stages of metabolism. These differences can be the result of the physiological development of the plant, plant part used, local climatic and soil conditions, seasonal variations, mixture of various compounds etc. (Regnault-Roger, 1997). Appropriate botanical pesticides (e.g. commercial neem formulations) are available and could be used as an excellent replacement to the synthetic chemicals being used presently by farmers. However, a coordinated resistance management program needs to be implemented with the involvement of pesticide industry, scientists and farmers and local pesticide regulatory authorities. At the same time, the judicious use of chemicals in conjunction with other control measures (e.g. biological control agents, resistant varieties, proper fertilization rates) is the best way to manage DBM and other pests of cruciferous crops. Indeed, the secondary metabolites with potential insecticidal properties and modern chemistry can play an important role in the development of novel insecticidal compounds. However, for pesticidal development from plant source, it is important to have their baseline toxicological and physiological data for regulatory and policy framework, development of commercial product for sustainable pest management in long run. Chemical synthesis of insecticides and baseline toxicological information will/may lead to design of novel compounds with reduced toxicity and selectivity (Dow AgroSciences, 2000). Phyto-secondary metabolites can serve as model compound for the development of synthetic derivatives e.g. development of nicotinoids based imidacloprid (Chitwood 2002, Park *et al*., 2005). Both synthetic derivatives and natural insecticidal plant extracts may serve a great purpose in the sustainable pest management of *P. xylostella* and other agricultural pests along with safety to environment and humans.

As broader picture has emerged/emerging with the new technologies that secondary metabolites have important ecochemical functions in the defense of plant insect pest and diseases. Further exploration, modification and then incorporation into their defense system will help in solving the problems faced in agricultural production (Hartmann, 1991). Recent advances in biotechnology and molecular biology have showed that plant will continue to contribute a lot in finding chemical entities. Through metabolic engineering, the endogenous biochemical pathways can be altered resulting in generation of transgenic crops with targeted objectives (Kinney, 1998). During last few years plant cell cultures have been intensively used for the production of commercial plant secondary metabolites e.g. pharmaceuticals, agrochemicals, flavours etc. (Whitmer *et al*., 2002). However, little success has been achieved. In other words making plants system stronger against insect pests and diseases. Basic toxicological information can be exploited for development of knowledge database and novel products. The use of molecular biology and metabolic engineering holds a promise for the future insecticidal development. However, there are missing links which need to be filled such as acceptability, impact on human and environment as many pathways and mechanisms are unknown. The information generated will give a better understanding with tremendous impact on discovery and development of novel insecticides. Initially, the effect is likely to be evident in the safety and efficacy and later, it will probably reduce both the time and cost of getting crop protection products to market. The knowledge thus gained will be helpful in the development of effective and safer insecticides.

CONCLUSION

Inhabitation of insects in food crops is one of the bottlenecks in low productivity and, therefore, it becomes essential to protect the crop form the insect infestation. The cole crops are infested by diamondback moth from nursery till harvest jeopardizing the quality of the marketable produce. Many innovative farmers in different parts of the world are using insecticides from locally available plant sources for the management of this pest. The literature survey showed that secondary metabolites from plant origin play an important role in the management of *Plutella xylostella*. Crop protections companies are also utilizing phytochemical information for designing safer and effective chemicals for sustainable insect pest management. Nevertheless, more can be done to upgrade our understanding on these plant based insecticidal sources and transferring this knowledge to the individual grower.

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