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Diamondback Moth *Plutella xylostella* (Linnaeus, 1758) (Lepidoptera: Plutellidae); A Real Menace To Crucifers And Its Integrated Management Tactics

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ABSTRACT

The diamondback moth (DBM), *Plutella xylostella* (Linnaeus, 1758) (Lepidoptera: Plutellidae), is a severe and most destructive pest of cruciferous vegetables in many parts of the world, including Nepal. The natural history and ecology of the diamondback moth are summarized here, along with appropriate management options. Caterpillar is the most devastating stage of DBM that matures and causes "windowing" damage, leaving only the epidermis. Biological control, cultural practices, effective chemical control, botanical pesticides, and host plant resistance are the most viable options. Insecticide abuse and resistance concerns are likely to persist, as numerous research-based outcomes have proven that none of these measures will suffice independently. However, these techniques can complement each other and result in a better long-term management system when combined. This review highlights the integrated eco-friendly management strategies for DBM and other cruciferous insect pests. Integrated Pest Management (IPM), which focuses on sustainable production, has shown promising results. Modern management techniques include genetic modification, use of parasitoids, modified cultural methods, the precautionary application of chemicals, resistant cultivars, fungal, bacterial (Bt. based biopesticides), and viral entomopathogens, etc., which are found to be more effective and eco-friendlier.

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Introduction

Cruciferous vegetables are significant winter crops widely cultivated in mainly hot and mild regions around the globe, producing 50.7 million metric tons. Crucifers contain a high concentration of biologically active substances (Phytochemicals) that positively impact human health by lowering the risk of cancer through oxidative stress prevention, inducing detoxification enzymes, stimulating the immune system, and lowering oxidative stress (Imran, 2018). Vegetable cultivation seems to be one of the most productive businesses for food security and cash generation in the city's proximity, where agriculture is the primary source of income and livelihood (Rai et al., 2019). Commercial farming is becoming more popular day by day in Nepal (Shrestha et al., 2018). Over the last two decades, intensification of agriculture and increased production of Cruciferous Brassica vegetable crops have increased the pest status of the diamondback moth (DBM), Plutella xylostella (Linnaeus, 1758) (Lepidoptera: Plutellidae), (Furlong et al., 2013). DBM is one of the most extensively researched insect pests of crucifers globally, but it is also one of the most challenging pests to control globally and in Nepal. DBM is a remarkably invasive species (Sarfraz, 2019). So, it is a big challenge to prevent the threat of DBM to reduce the yearly substantial economic loss of the Nepalese farmers and the agricultural business to ensure food security. This study aims to identify and suggest the most effective and eco-friendlier integrated management strategies for DBM management.

Origin and Distribution

DBM is a dangerous insect of cruciferous crops worldwide (Talekar and Shelton, 1993). According to (Kfir, 1998), DBM was originated in the Mediterranean region, and spread throughout the world with cultivated brassicas as shown in figure 1. Non-cruciferous crops like *Amaranthus viridis* have also been affected (Bhattarai et al., 2012). The diversity of parasitoids attacking *P. xylostella* and the availability of a considerable number of indigenous. *P. xylostella* was first discovered in North America in Illinois in 1854 (Capinera, 2002). It is reported to be a recurring problem in the southern United States, where some of the nation's leading Brassica vegetables, such as collards and cabbage, are grown (Zalucki et al., 2012a). The evidence, such as the presence of various indigenous plants belonging to Brassicaceae, also possess diversified abundance of DBM parasitoids, and the bisexual form of the parasitoid *Diadegma collaris* which is used for its control in nature which was reported as the first natural control of DBM(Kfir, 1998).

Insect Biology

The growth and development of *P. xylostella* have been reported to occur in between 8 and 32°C, with the best chance of survival at 14°C requiring 41 days to complete a generation.

Egg

Mating occurs within a few hours of emergence and lasts approximately 1-2.5 hours. Males copulate more than twice in their entire lives. But unlike females, they mate only once (Ramzan et al., 2019; Wang et al., 2005). According to the research findings, the eggs were yellow and pale green; the female laid approximately 200-210 eggs on the lower surface of the leaves to protect them from wind and rain (Talekar and Shelton, 1993). The small (0.44 x 0.26 mm) yellowish eggs can be easily seen in the field (Sarfraz, 2019). The hatching time for an egg was two to four days. Tiny new larvae with a whitish-yellow to pale green color began feeding on the underside of leaves shortly after emergence. The eggs are reported to be laid singly or in clusters of two to eight in depressions on the foliage's surface, with 60% of the eggs being laid on the upper surface as shown in figure 2 (Philips et al., 2014a).

Larva

The larval period is reported to be of ten to fifteen days, with chances of varying due to the dependence of its maturation on weather and a few other ecological factors (Imran, 2018). There are four instars of the diamondback moth. Four instars of DBM are reported with an average development duration of approximately 4.5, 4, 4, and 5 days respectively. Both ends of the larval body taper, with a few prolegs protruding derived from the rear end, creating a distinct “V”. Prolegs come in five pairs (Gululatu Laxman, 2017). The severe attack and feeding of *P. xylostella* first instar larvae from seedling to crop harvesting reduces the quality and quantity of cruciferous crops (Gowri and Manimegalai, 2016; Ramzan et al., 2019). Newly hatched larvae had a light brown head, whereas completely developed caterpillars were pale green and 10 millimeters long as shown in figure 3. Because of their small size, the first instar larvae were leaf-mining and challenging to see. The larva's body and head capsules were yellowish-green and light brown. The second instars are more active and larger than the first and change into the third instar after 3-4 days. The development of second instar larvae into third instar larvae takes 3-4 days, light yellow. The third instar feeds more vigorously than the first and second instars, and after 4-5 days, it transforms into the fourth instar. The fourth instar larvae were dark green (Ramzan et al., 2019).

Pupa

This pest went through two dormant stages: pupa and prepupa. The larva showed slow movement and reduced feeding during the pre-pupal stage, which lasted about 1 to 3 days on average, together with a mean of 1.45 ± 0.65 days. Finally, the pre-pupa scene transitioned into the pupal stage, which lasted 1 to 3 days (Gowri and Manimegalai, 2016), as shown in Table 1 Pupation takes place inside a loose silk cocoon that forms on the abaxial or upper leaves as shown in Figure 4. The whitish pupa measures 7 to 9 mm in length. The cocoon lasts roughly 8.5 days on average (range five to 15 days) (Gautam et al., 2018).

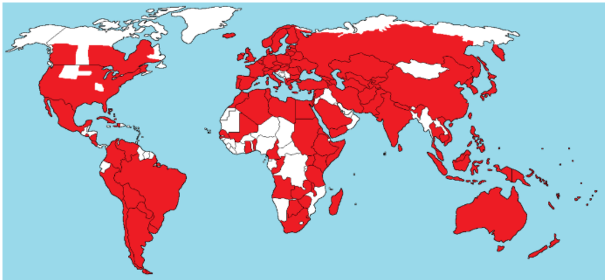

Figure 1. Biogeographical distribution of Plutella xylostella (Fjga, 2014)

Figure 2. Eggs of DBM

Figure 3. Larva of DBM

Adult

The grown-up adult is a little brownish moth with prominent antennae that seems to be tiny and thin as shown in Figure 5. It is around 6 mm in length and has a broad cream or light brown stripe running down the back (Capinera, 2000). Adults of Diamondback Moths emerge after twilight and remain active until night (Harcourt, 1954). The majority of adults appear within the first 8 hours of the photo phase (Pivnick et al., 1990), with mating taking place at dusk on the same day the adults appear. Adult Diamondback moths have a maximum wingspan of around 3/4 inches and are brown to grey. The average lifespan of a female is 16 days, and that of a male is 12 days. On the day of emergence, about 95% of females begin laying eggs; this process takes ten days, and the number of eggs deposited per female varies between 159 and 288 (Ooi and Kelderman, 1979). The folded wings create an appearance of light-colored diamond shapes along the backs of the wings, where they meet when they are at rest (Hutchison, 1980). Female moths begin laying eggs immediately after copulation; The female lays 11-118 eggs during the ovi-position stage, which lasts four days (Harcourt, 1954; Talekar & Shelton, 1993).

Figure 4. Pupa of DBM inside silken cocoon

Figure 5. Adult DBM
(Photo: courtesy of Jean-Francois Landry, Ottawa Research and Development Centre)

Table 1. Life cycle of Diamondback moth, Plutella xylostella on mustard under laboratory condition

Life stages observed in Laboratory (25±2°C)	Duration (in days)
Oviposition period	6.5±0.41
1st instar	5.0 ± 0.55
2nd instar	3.5 ± 0.60
3rd instar	4.0 ± 0.45
4th instar	3.5 ± 0.85
Total Larval period	15.50 (12-17)
Pupa Period	4.50 ± 1.11
Life Cycle of Male (♂)	32.5 + 0.43
Life Cycle of Female (♀)	35.5 ± 4.32

(Modified from Ahmad et al., 2008)

Insect Habit, Nature of the Damage, and Yield Loss

DBM is prevalent from early spring to late autumn, with the maximum in June - August. The insect attacks almost all crucifers at all times throughout the growing season (Sakai, 1986). Larval feeding causes excessive plant damage. Despite their small size, the larvae can be quite dangerous under severe infestations, resulting in the complete removal of foliar tissue except for the leaf veins (Capinera, 2000). This is especially harmful to seedlings and may interfere with the head formation in cabbage, broccoli, and cauliflower. Caterpillars that are very small cause leaf-mining (pin-holing) damage, and as they mature, they cause 'windowing' damage, leaving only the epidermis. As the plant tissue grows, these 'windows' tear, leaving holes in the leaves (Bentley et al., 2022). DBM populations in high numbers cause leaf tattering and can stifle growth during the early stages of plant development. Caterpillars can also tunnel into cabbage heads and brussels sprouts and feed within broccoli and cauliflower florets (Martin, 2006). Pesticide sprays are almost useless once the caterpillars are inside the developing head, sprouts, or florets (Kahn et al., 2009). Caterpillars and cocoons on and inside heads, sprouts, florets, and fouling caused by caterpillar frass (droppings) and feeding damage to heart tissue or wrapper leaves render the product unfit for sale (Laufer, 2010). Even if the amount of plant tissue removed is minimal, larvae in florets can result in total rejection of produce. A single outbreak in California resulted in losses of more than US$6 million (Shelton et al., 2000). Globally, a conservative estimate of the total costs associated with *P. xylostella* management was $4–5 billion per year (Zalucki et al., 2012b). However, an estimated 31% loss has been reported (Macharia et al., 2013). Some studies have foresighted the occurrence of losses up to 100% when left unchecked(Ayalew, 2006; Canico et al., 2019). According to reports from Botswana, as well as personal observations made during fieldwork in 2014 and 2015, DBM costs the global economy an estimated US$4 -5 billion annually. Still, its impacts on local biodiversity and habitats in exotic ranges are unknown (Sarfraz, 2019).

Present Status and Threat of DBM in Nepal

Cabbage is a popular cruciferous vegetable crop consumed for various purposes in the world and Nepal. The Diamondback moth (*Plutella xylostella*.L.) is a major pest in Nepal, inflicting massive losses in cabbage farms every year. Specific resistant cultivars like as G 9101 and G 9619, as well as transgenic lines, are successful in the Nepalese context, but are not widely used by Nepalese farmers (Parajuli and Paudel, 2019b). They cause a heavy loss in cabbage production in Nepal (Katuwal et al., 2012). The growth of plants is affected and reduces production and yield by 31-100% (Parajuli and Paudel, 2019b)

Economic Threshold Level (ETL) of DBM

The plants were found tolerating 20 larvae/plant populations for seven weeks after transplanting before suffering severe economic damage and yield reduction (CABI, 2021). According to crop loss estimation studies conducted in Bangalore, the Economic Threshold Level (ETL) for DBM is considered if a population of four or more medium-sized larvae (third or fourth instar) may make a seedling non-transplantable and a population of ten medium-sized larvae/plant up to one month after planting and twenty medium-sized larvae/plant between one and two months after planting necessitated insecticide application (Rahardjo and Tarno, 2018).

Management Strategies

Integrated Pest Management (IPM) refers to the careful consideration of all appropriate pest control strategies and the subsequent integration of appropriate measures that prevent the development of pest populations, maintain pesticides and other interventions to economically justified levels, and mitigate or eliminate threats to human health and the environment (Prokopy and Kogan, 2009,). IPM promotes natural pest management mechanisms and stresses the growth of a healthy crop with the least possible disturbance to agro-ecosystems (Ekström and Ekbom, 2011). To enjoy the fruits of IPM, the Nepalese government-approved IPM as part of its plant protection policy in 1990, but the program was not implemented at the farm level until 1998 due to a shortage of skilled human resources and funds. In 1997, Nepal introduced Community IPM (CIPM), and the first project, the Farmer's Field School (FFS) in rice, was implemented in 1998 (Westendorp and Biggs, 2021). The Chitwan was the first to apply IPM practices. The Ministry of Agriculture and Livestock of Nepal has prioritized and encouraged IPM approaches in most communities (Parajuli and Paudel, 2019b). Pest management is more feasible by adopting the resistant cultivars imparting chemical, cultural, and biological controls (Magallona, 1986).

Cultural Control

Intercropping cropping, selection of resistant varieties, clean cultivation, crop rotation or maintenance of host free season, irrigation, fertilizer use, sowing and harvesting time, destruction of crop residues, weeds, destruction or provision of alternate hosts or volunteer plants, and so on are examples of cultural tactics for DBM.

Intercropping and Trap Cropping

Monocultures with a narrow genetic base originate from the usage of new high-yielding crop cultivars, which are more prone to pest losses. This is because monoculture reduces the diversity of pest species, which have a higher capacity for population growth without competition (Talekar et al., 1986). In Taiwan, Talekar et al. (1986) intercropped cabbage with 54 different crops to control DBM. Intercropping tomato, dill (*Anethum graveolens* L.), safflower (*Carthamus tinctorius* L.), garlic (*Allium sativum* L.), oat (*Avena sativa* L.), and barley (*Hordeum vulgare* L.) reduced DBM damage to cabbage. Intercropping cabbage with non-host plants like onion and tomatoes can aid in replacing insecticides like chlorpyrifos along with a boost in the yield and quality of cabbage heads produced (Warwick et al., 2010). According to Srinivasan and Moorthy (1992), the most effective planting pattern for effective DBM management was found to be paired mustard rows at either end of 25 cabbage rows. As cabbage is susceptible to insect attack shortly after emergence, it is critical to plant the mustard 15 days before planting the cabbage to ensure adequate trap crop foliage (Srinivasan and Moorthy, 1991). Buranday and Raros (1975) discovered that the intercropping of tomato with cabbage suppressed DBM larval infestations in the Philippines and Malaysia. The authors further noticed the repelling action of adult DBM away from mustard plants in response to volatile compounds from tomato plant intercropped in the field.

Field sanitation

In Vietnam, the land is typically plowed over and exposed to the hot sun for a week before cultivation to clean up DBM sources (Guan-Soon, 1990). DBM infestations are found to be significantly reduced when irrigation is controlled with sprinklers as the sprays of water disrupts the moth's mating and oviposition (Talekar et al., 1986). Field sanitation also increases the chances of drowning of young larvae during periods of heavy rain.

Resistant varieties

Early maturing cauliflower varieties were tested for *P. xylostella* resistance in a farmer's field near Varanasi. Based on the DBM infestation index and mean relative yield, Pusa Keiki and Pusa Deepali were highly resistant. In contrast, early Kunwari, Pant Gobhi-3, Early Pusa synthetic, Sel-327, Pusa hybrid-2, and Pant subbra were moderately resistant. The least tolerant reaction to DBM was observed in Pusa Sharad and Sel-328 (Mukerji, 2006). The susceptibility of various crucifer crops to *P. xylostella* attack varies. Some resistant vegetables include mustards, turnips, and kohlrabi (Radcliffe and Keith Chapman, 1966). Leaf waxes and related chemicals are a significant component of resistance, eliciting non-acceptance behavior in *P. xylostella* neonate larvae and preventing development (Eigenbrode and Shelton, 1990). Due to a genetic mutation, these varieties have shiny green or glossy leaves, allowing larvae to spend more time exploring and less time eating which can be benefitted by predators. In addition to conventional breeding programs, biotechnology-created resistant varieties are valuable in advanced pest control efforts for *P. xylostella*. A few Brassica species, for example, have been engineered to express the *Bacillus thuringiensis* Cry1 insecticidal protein from the soil bacterium *Bacillus thuringiensis* (Shelton, 2012). With high levels of tolerance to *P. xylostella* and other lepidopteran pests, these plants have enormous potential; however, biotechnology is unlikely to be a viable option soon, given the current unfavorable public perception of genetically modified organisms and the difficulties in bringing them to market (Shelton, 2012).

Mechanical Control

Blue-light traps can capture large amounts of adult DBM. In fine-mesh netting houses, planting crucifers such as Chinese kale, pakchoi, Chinese cabbage, and cabbage yielded similar results. DBM, along with several other common pests, were well-protected. Yellow sticky traps, in conjunction with other traditional approaches, are found effective in controlling DBM in Thailand (Guan-Soon, 1990).

Biological Control

Natural enemies such as parasitoids, predators, and pathogens attack *P. xylostella* at all times of the life cycle, lowering densities to harmful thresholds. Pest outbreaks are commonly caused by a lack of efficient natural enemies in a given location or by pesticides that disrupt these natural enemies (Philips et al., 2014c). If natural enemies (both native and imported) are conserved and their presence is promoted, they can help keep the pest at a tolerable level. Early in the season, when the diamondback moth is present in low numbers, habitat conservation and avoidance of broad-spectrum insecticides can help in maintaining natural enemies in more numbers that will help keep diamondback moth and aphid populations under control later in the season. At various stages of its life cycle, the diamondback moth is preyed upon by different natural enemies. Moths are eaten by birds and spiders, while caterpillars are attacked by ants, lacewings, wasps, and parasitic wasps, among others (*Diamondback Moth (DBM) | Infonet Biovision Home.*, 2019).

Parasitoids and Predators

Pesticide overuse and abuse against DBM have been a significant issue in many areas of Thailand and are on the verge of becoming throughout the world. This improper use of pesticides will harm farmers' health, contaminate soil and water, and result in excessive vegetables. Furthermore, this over-reliance on pesticides kills natural enemies of DBM and other pests. Studies were intended to raise awareness of the diversity of DBM parasitoids present in Thailand and encourage improved biological control and integrated pest management efforts (IPM) (Rowell, 2021).

Parasitoids are parasitic insects that feed on other insects. The control of *P. xylostella* is dependent on hymenopteran parasitoids. Ninety different parasitoids attack *P. xylostella*. Six parasitoids species attacked *P. xylostella* eggs, larvae were assaulted by 38 parasitoids, and 13 parasitoids attacked pupae (Philips et al., 2014c). Diamondback moths are attacked by a swarm of most common parasitic wasps like *Cotesia, Diadegma, Diadromus,* and *Oomyzus.* Egg parasitoids are tiny wasps that lay eggs within insect pests and develop into adults. In Thailand, at least one DBM egg parasitoid insect, *Trichogrammatoidea bactrae*, is found naturally (Rowell, 2021). The Department of Agriculture, Thailand, reared and mass released this parasite in the field in the mid-1880s and 1990s, and the range of parasitism in unsprayed experimental areas is 16–45 percent of diamondback moth eggs; findings indicate that this parasite dominated DBM but was destroyed by chemical spray (Imran, 2018). The larval parasitoid *Cotesia plutellae* is used to monitor diamondback moths (DBM). In Taiwan, *Plutella xylostella* L. released in a glass house without insecticides significantly impacted the larval stage (Kwon et al., 2006). Only the larval stages of DBM are where specific DBM parasitoids lay their eggs. The adult female parasitoid is found to lay one or two eggs inside the DBM larva's body. The parasitoid larva is reported to hatch and develop inside the DBM larvae without killing them. The larva then dies and forms a cocoon. Some species, such as the *Cotesia plutellae*, make their cocoons outside the dead or dying body of a DBM larva (Kahuthia-Gathu, 2017). In contrast, Others build their cocoons inside the DBM cocoon (as does *Diadegma semiclausum*). As long as DBM hosts are available, the adult parasitoid (wasp) escapes from its cocoon ,mates, and the cycle repeats (Rowell, 2021). *Diadromus collaris* is a pupal parasite having a life cycle of 15 days that measures 6–7 mm in length and only lays eggs in the pupal cocoon. This species can be found in the provinces of Chiang Mai and Petchaboon in Thailand. At the University of Maejo, parasitism on diamondback pupa was tested, and it was found to be 9–30% (Imran, 2018). The diamondback moth, *Plutella xylostella,* is parasitized by *Oomyzus sokolowskii*, a larval-pupal parasitoid. In a host stage preference survey, the parasitoid parasitized both larval and pupal stages but clearly preferred larvae over prepupae or pupae (Wang et al., 1999).

Among predators, spiders, wasps, coccinellid beetles, pentatomid bugs, phytoseiulus mites, Chrysopidae, ophionea beetles, and bird predators are essential. It has been observed to build up to a later phase of the crops, causing 68-70% larval mortality. Although predators have been suggested as mortality factors, they have not been exploited against DBM (Mohapatra, 2017). The DBM pheromone blend, larval frass, and green leaf volatiles of crucifers equally attracted predators, including *Chrysoperla carnea* Stephens (Neuroptera: Chrysopidae) (Muhammad, 2005; Reddy et al., 2004).

Enrichment of natural enemy fauna and flora could be an effective method for integrated pest control (Chiang, 1980; Sastrosiswojo and Sastrodihardjo, 1986). As a result, attempts are being made to conserve and further augment *Diadegma eucerophaga*, such as selective insecticides, the estimation of action thresholds, and the manipulation of cabbage cultivation by intercropping systems (Sastrosiswojo and Sastrodihardjo, 1986).

Microbial control

Several fungi, nematodes, bacteria, and viruses attack the diamondback moth in the field. With the discovery and development of novel entomopathogens, microbial pesticides in crop protection are expanding (Muhammad, 2005).

Bacterial: Bacillus thuringiensis, or *Bt*, is a soil bacteria that can sporulate and produce a crystalline protein (cry protein). This insecticidal poison can be used to destroy most Lepidopteran larvae, including DBM larvae. Though dipteran and coleopteran species are also affected, the toxin does not target beneficial insects like broad-spectrum insecticides because it is so host-specific (Höfte and Whiteley, 1989). δ-endotoxins produced by the *Bacillus thuringiensis* (*Bt)* soil bacterium are highly specific to insect pests and are used as biopesticides to combat various pest species, including DBM (Rekha et al., 2011; Srinivasan, 2012). Among Bt strains, Bt var. aizurai and Bt var. Kurstaki is effective, particularly against DBM. Bt products are registered for brassica crops that kill only caterpillars and are very valuable in managing diamondback moths (DBM). These products include Dipel®, Delfin®, Halt®, Xentari®, Novosol®, Agree®, Biobit® and Thuricide®. Bt is applied at 500gm ai /ha at a ten-day interval (Liu et al., 2014). Integrating B. thuringiensis-based products and traditional, non-conventional, and azadirachtin-based insecticides will enhance *P. xylostella* control. Rotation or the simultaneous use of two or more products of different origins seem adequate to prevent *P. xylostella* from developing resistance to any single insecticide (Seal, 1995). Recent studies have shown that natural enemies of DBM can help delay the development of resistance to the Cry-toxin developed by induced *Bt* crops, thus providing a favorable environment for natural enemies, which is an outstanding IPM tool (Liu et al., 2014).

Table 2. Natural enemies of diamondback moth (*Plutella xylostella*)

S.N	Species	Stage	Remarks
1	*Trichogramma chilonis* Ishii (Trichogrammatidae:Hymenoptera)	Egg	51.5-57.0% parasitization when released @ 2 lakhs/ha
2	*Trichogramma armigera* Nag (Trichogrammatidae: Hymenoptera)	Egg	-
3	*Trichogrammatoidea bactrae* Nagaraja (Trichogrammatidae: Hymenoptera)	Egg	30% parasitization
4	*Cotesia (Apanteles) plutellae* Linnaeus (Braconidae: Hymenoptera)	Larva	18-75%parasitization. Peak activity - July and October
5	*Diadegma fenestrale Holmgren Diadegma collaris* Gravenhorst	Pupa	66 to 80% parasitization
6	*Diadegma semiclausum,* Horstmann	Pupa	68% parasitization
7	*Tetrastichus sokolowskii* Kurd (Eulopidae: Hymenoptera)	Larval Pupal	Endoparasitoid, Parasitization – 30 to78% Peak activity August-September
8	*Brachymeria exacarinata* Gahan (Chalcididae: Hymenoptera)	Pupa	Endoparasitoid parasitization-20 to 60%peak activity-August
	II. Predators		
1	*Chrysoperla carnea* (Chysopidae: Neuroptera)	Eggs and Larva	Single larva predate 74.67 eggs and 57.0 first instar larvae
2	*Coranus* sp. (Reduviidae: Hemiptera)	Larva	Single adult predate12 DBM larvae/day.12 DBM larvae/day. Optimum predator prey ratio 1:6
	Ants		
1	*Tapinoma melanocephalum* (Formicidae: Hymenoptera)	Larva	Sprinkling 5% jaggery solution encourages ant activity
2	*Camponotus* spp. (Formicidae: Hymenoptera)	Larva	-
3	*Pheidole* sp. (Formicidae: Hymenoptera)	Larva	-
	Birds		
1	Yellow wagtail (*Motacilla flava*)	Larva	Peak activity during cold seasons
2	Cattle egret (*Bulbueus ibis*)	Larva	-
	Pathogens		
1	*Bacillus thuringiensis var kurstaki*	Larva	
2	Nuclear polyhedrosis virus(NPV)	Larva	
3	Granulosis virus (GV)	Larva	
4	*Paecilomyces farinosus* (Fungus)	Larva	Spraying fungal inoculum @ 1.7 x 10^8 spores/ml at a weekly interval from initiation of primordia
5	*Beauveria bassiana* (Fungus)	Larva	Spray of conidial
6	*Zoophthora radicans Fre* (fungus)	Larva	-
7	*Vairiomorpha sp*. (protozoa)	Larva	Spraying inoculum @1.2 x 107 spores/ml reduces the DBM population by 55.7%
8	Nematode (DD-136)	Larva	Spraying inoculum @1.2 x 107 spores/ml reduces the DBM population by 55.7%

(Modified from Lingappa et al., 2004).

Fungal: The fungi *Zoophthora radicans* and *Beauveria bassiana* are the most successful against DBM larvae. The use of mycoinsecticides dependent on *Beauveria bassiana* for the management of DBM is gaining popularity. After 3-7 days, when this pathogen is applied at a rate of 3*10^6 conidia m^L, the DBM mortality rate is 100% (Sarfraz et al., 2005). The fungus is successfully transmitted (horizontal/passive transmission) to healthy moths and larvae feeding on plants by those contaminated moths. Transmission rates are similar when sporulation cadavers generating Z. radicans or B.bassiana conidia (Mohapatra, 2017).

Virus: Nucleopolyhedrovirus (NPV; *Alpha Baculovirus spp*.) and Granular Viruses (GV; *Betabaculovirus spp*.) are two varieties of lepidopteran-specific viruses diamondback moth is vulnerable to, and strains of both are commercially active. Px GV was found to be more effective than available chemical insecticides at controlling diamondback moth populations on kale in Kenyan experiments (Kibata et al., 2004). In glasshouse studies, PxGV sprayed at a rate of 8.9 x 10^{13} OB/ha effectively controlled a synchronized population of diamondback moths (Kadir, 1990). DBM on kale were controlled with 82 and 90 percent infection rates for second and first instars, respectively, using a Kenyan isolate of PlxGV (Nyathuna, Nya- 01) treated in the field at 3.0-1013 occlusion bodies (OB) ha^{-1}. The NPVs isolated from *Anagrapha falcifera* (AfNPV), *Autographa californica* (AcNPV), and *Galleria mellonella* (GmNPV) infected DBM as well, although their potency was moderate to low (Mohapatra, 2017).

Nematode: Out of the 24 known entomopathogenic nematode families, Steinernematidae and Heterorhabditidae in the order Rhabditida have been the most extensively studied as biological control agents against the diamondback moth in Malaysia (Gurr et al., 2018). Diamondback moth larvae are controlled by a cell of *Xenorhabdus nematophila* found in Steinernema *carpocapsae* (Boemare et al., 1997; Imran, 2018).

Diamondback moth larvae are best controlled with a cell-free solution containing bacterial cell suspension or nematode toxins (Mahar et al., 2004; Imran, 2018). Using nematodes to control diamondback moth can theoretically reduce resistance development in diamondback moth populations to *B. thuringiensis* products. Still, repeated applications of nematodes will probably be ineffective in attaining control (Baur et al., 1998).

Botanical pesticides

Botanical pesticides can be a viable and sustainable alternative. Several pieces of research have proved the pesticide properties of phytochemicals. They are easily degradable; maintain soil properties, and safe for the environment and humans. *Zingiber officinales, Piper retrofractum, Allium ativum, Solanum* spp*, Citrus sinensis* peels, and turmeric rhizome were more successful against *P. xylostella P. xylostella* than synthetic insecticides (Rahardjo and Tarno, 2018). Plant products from the Meliaceae family have been widely used to control insect pests, particularly products from the neem tree, *Azadirachta indica*. The neem tree does not grow in South Africa. Still, the intimately related syringa tree Melia azedarach neem- and syringa-derived botanical pesticides were found to have adverse effects on the development, reproduction, and survival of *P. xylostella*. These botanical pesticides are also reported to reduced feeding and oviposition, which are essential factors in pest control (Charleston, 2004). Annosom 1% w/w (*Annona* spp. extract) and Neemix (60% w/w *Azadirachta indica* extract) are found to be effective botanical insecticides (Parajuli and Paudel, 2019b). Plants used in a study by (Abuzid, 2011) were damaged mechanically, by detached insect body parts (thorns on the hind legs of grasshoppers), by aphids, and by larvae of DBM. Results of the Y-olfactometer test indicated that the DBM adults elicit different responses to odors released from Chinese mustard plants injured in different ways (Abuzid, 2011).

Insect Growth Regulators

Though Diflubenzuron possesses strong antifeedant properties against second and third instar larvae (Srinivasan and Moorthy, 1992), teflubenzuron (45 g. a.i./ha) and flufenoxuron (20 g a.i./ha) were found more effective(Peter and Sundararajan, 1991). Two applications of teflubenzuron (90 g a.1./ha) combined with urea (2 %) decrease the larval population from 4.08 to 0.24 larvae/head and records the highest (17.53 t/ha) cabbage yield due to synergization of Insect Growth Regulators (IGR) to inhibit chitin synthesis and feeding in DBM larvae. Three sprays of flufenoxuron (80 g a.i./ha) greatly reduced DBM infestation and improved cabbage yield at 3, 7, and 10 days after application compared to fenvalerate 40 g a.i./ha, Delfin (Bt) 50 WG 0.5 kg/ha, and cartap hydrochloride (400 g a.i./ha). Lufenuron, sprayed at a rate of 20 g a.i./ha was found effective in decreasing the P. xylostella populations, significantly increasing marketable heads (Lingappa et al., 2004).

Genetic Control

Genetic control entails modification of the heredity mechanism. An outstanding example of genetic control is the sterile male method, sterilizing natural populations by chemosterilants and other genetic tactics. The potential for developing varietal resistance to DBM in brassicas has not yet been completely realized. Plant biochemical and morphological characteristics have also been unsuccessful. Resistant variety production remains a significant challenge for biochemists and plant breeders in South Africa, considering its potential as a non-chemical DBM control tool. No studies have identified chemical compounds or genes that could be used to make brassicas non-preferred hosts for DBM (Gautam et al., 2018).

Sex Pheromones

DBM has the highest level of insecticide tolerance. The prevalence of resistance in pest populations is primarily due to selection pressure from pesticide use (Georghiou, 1980). Pheromones may be used to combat insect pests that were immune to insecticides. The pheromone decreased the frequency of application of insecticides were used to combat DBM, but it had little effect on other pests (Nemoto et al., 1992). The use of synthetic sex pheromones to manipulate insect pest behavior has recently received a lot of attention. In 1970, sex pheromones were used for the first time to monitor the pink bollworm, *Pectinophora gossypiella*. In field trials conducted in 1987 and 1988, a synthetic sex pheromone dispenser (SSPD) comprising (2)-11-hexadecenal: (Z)-1 1-hexadecyl acetate was utilized to determine the communication disruption mechanism for controlling the diamondback moth, *Plutella xylostella* (L.), on cabbage. In the Atsumi Peninsula, fields for the SSPD environment were flattened by strong winds, and in Sitara, the northern district of Atsumi, fields were undulating mountainous regions. Compared to the area without SSPD treatment, the DBM adult population density in the field with SSPD treatment was found to drop by 92 to 97 percent in Atsumi and 95 percent in Sitara. These results supported the feasibility of the information disruption strategy for DBM control (Ohno et al., 1992). In the greenhouse, sex pheromones were also effective in controlling *P. xylostella* (Hou et al., 2001). Field trials have shown that adjusting the component ratios and dosage rates of sex pheromones (Wang et al., 2013), the usage of half-bell-shaped septum dispensers, and the deployment of wing-shaped traps (Kang et al., 2011) will increase their efficacy.

Host Plant Resistance (HPR)

The basis for pest control should be host plant resistance, but there is no appropriate resistant germplasm (Kennedy, 2008). This is particularly true for Lepidoptera and Coleoptera, two of the largest and most destructive insect orders. Intensive insecticide use has raised concerns about crops like brassicas in developed countries. Growers desire pest management strategies that are simple to adopt and labor-intensive in both developing and developed countries (Shelton, 2007). Javed and Mukhtar (2017) reported that DBM damage and population were lowest on White Diamond and Fd-4 cultivars, relative to Snow Mystique, Siria F1, and White Castle cultivars, which had the most severe DBM damage and population. White Diamond and Fd-4 cultivars are recommended for cultivation since they suffered less loss. The development and deployment of insect-resistant brassicas can aid in the achievement of its objectives and serve as an important new method for brassica IPM efforts (Grzywacz et al., 2010). Plant material with reliable endogenous DBM resistance can eliminate the need for broad-spectrum chemicals, often preventing introduced and endemic natural enemies from reaching their maximum potential. The susceptibility of crucifer crops to attack by the diamondback moth differs. Mustard, turnip, and kohlrabi are resistant crucifers, but their tolerance isn't as well established as for imported cabbageworm and cabbage looper (Grzywacz et al., 2010). Varieties also differ in their susceptibility to diamondback moth damage, and the presence of leaf wax is a significant factor in this resistance. Glossy forms, which lack the waxy blossom and are therefore green rather than grayish-green, are to some extent harmless to larvae. Larvae simply invest more time looking and a shorter eating period on shiny forms. Introduced cabbageworm larvae and cabbage aphids are also less common in glossy species, although there are more (Grzywacz et al., 2010).

Chemical Control

An experiment was conducted in the West Bengal cabbage ecosystem in 2013-2014 and 2014-2015 to investigate novel insecticides and biopesticides on DBM and their effect on natural enemies. A bioefficacy study showed rynaxypyr as the most effective chemical in reducing larval population (96.41%), followed by flubendiamide (94.86%) and spinetoram (92.62%). Novaluron and indoxacarb have resulted in a significant decrease in the larval population (92.04%). As cruciferous vegetables are cultivated all year, they provide an easily accessible food source for many pests, including DBM, due to which these crops are subjected to DBM damage all year (Sakai, 1981). Spinosad, Indoxacarb, and Emamectin benzoate are the most commonly used insecticides to control this moth (Zhao et al., 2006). Spinosad is the first member of the natural insecticide family with a high activity level while posing minimal human and environmental risk (Thompson et al., 2000). Due to its quick reproductive turnover and short lifetime, DBM has become the chief insect pest of crucifers. As the area under the crucifers has grown and DBM infestations have increased, so has the frequency with which insecticides are used to get rid of this pest.

Table 4. Main insecticides licensed for DBM control

Insecticide	Formulation
Tertiary Amine	SC
Cartap Carbamite	50SP, 2D
Methomyl Organophosphorus	45WP
Acephate	50WP, 5G
Chlorfenvinphos	5D
Chlorpyrifos-methyl	25EC
Cyanophos	50EC
Dichlorvos	50EC, 75EC
Prothiofos	45EC, D
Salithion	25EC
Tetrachlorvinphos	50WP
Trichlorfon	50EC
Spinosad	2.5SC
Fipronil	5SC
Novaluron	10EC

Where: EC=Emulsifiable Concentrate; SC= Suspension Concentrate; WP= Wettable Powder; SP= Soluble Powder; D=Dust, G= Granules; and figures indicate percent active ingredient in formulations (Modified from (Sakai, 1986)).

Insecticide Resistance and Management

Diamondback moth is a common lepidopteran pest of cole crops such as cabbage, collards, turnip greens, mustard greens, broccoli, cauliflower, and other Brassica species. Since the introduction of DDT in 1953, this insect has developed resistance to insecticides. Since then, DBM has become resistant to each new class of insecticide arriving on the market whenever those insecticides were used intensively and repeatedly to control a DBM population (Riley and Jr, 2009). New environmentally safe and less toxic pesticides are now on the market. Still, growers continue to use broad-spectrum pyrethroids, organophosphates, organochlorines, and a variety of other traditional insecticides which have built up resistance in the DBM. Diamondback moths have a long history of developing resistance to all insecticides that have been used to combat them. Resistance to insecticides and a loss of control are now standard, and crucifer production has become extremely difficult in some situations. High fecundity and reproductive capacity, quick generation turnover, a long growing season, and frequent insecticide application are all factors that influence the production of resistance in diamondback moths. In Bangalore, the first observation of a DBM population refusing insecticidal action was made in 1989 against deltamethrin and quinalphos. (Chandrasekaran and Regupathy, 1996; Saxena et al., 1989) used an F26 laboratory-reared population that had not been exposed to anything. Resistance to fenvalerate ranged from 66.70 to 100%, quinalphos from 45.50 to 92.3%, monocrotophos from 32.6 to 85.7%, carbosulfan from 14.3 to 55.2% , and cartap hydrochloride from 17.9 to 52.4%. Tolerance to carbosulfan, which was not commercially available at the time, was also found to be minimal. Surprisingly, tolerance to carbosulfan, which was not yet commercially available, was also minimal. DBM was the first agricultural insect to gain resistance to microbiological *Bacillus thuringiensis* pesticides, and it has since demonstrated resistance to nearly every pesticide, including newer groups like diamide. DBM is indeed considered as a very invasive plant (Sarfraz et al., 2005).

For successful decision-making, resistance monitoring is essential (Ginevan, 2002). Non-cruciferous crops can be rotated with the cruciferous crops (Geu-Flores et al., 2009). By following ETL, one can avoid excessive insecticide spraying. Use of Trap crops, Insecticide mixtures, Insecticides rotation regularly, use of Botanicals (neem), biopesticides (*Bt.*), *Diadegma semiclausum*, and *Cotesia plutellae* conservation and/or augmentation can be environment-friendly practices. Use selective insecticides, the Combined form of pyrethroids with 0.2 percent sesamum oil and honge oil, to promote natural enemy activity to control resistant populations,etc. can also be done (Lingappa et al., 2004).

Conclusion

The diamondback moth (*Plutella xylostella*.L.) is a major pest of cruciferous crops in Nepal, inflicting significant losses each year. The diamondback moth has become one of the most difficult insects to control because of its intrinsic biology and ecology and its large host range, which includes many crops. Although chemical control techniques appear to be used by almost all Nepalese farmers due to their ease of availability, medium low cost, low labor cost, and less tiring job, excessive chemical use is shortening human lives and, on the contrary, extending insect lives. The trend of extensive and unscientific insecticide use has resulted in a devastating loss in production (31%-100%) and economic yield (the US $4-US$5billion each year) and also resulted in environmental degradation in various ways. Integrated pest management strategies, including botanical, biological, and cultural approaches, and resistant cultivars, are hence successful. *Zingiber officinale*, *Piper retrofractum*, *Allium ativum*, *Solanum* spp., *Citrus sinensis* peels, and turmeric rhizome were more successful botanical insecticides against *P. xylostella* than synthetic insecticides. Parasitoids, especially *D. semiclausum* and *C. plutellae*, have been tremendously successful in controlling diamondback moth populations, providing a model for the basics of a successful IPM program. Importation of these or functionally similar biological-control agents can serve as the basis of a management program. *Diadegma* spp. is one of the most effective biological control agents. Hence, the use of botanical pesticides and bio-control agents should be prioritized to overcome the hazards of chemical methods. Also, IPM strategies should be emphasized and implemented for sustainable and effective management of DBM and other crucifer pests.

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