CRITICAL REVIEW ON PAST, PRESENT AND FUTURE SCOPE OF DIAMONDBACK MOTH MANAGEMENT

Thinley Jamtsho, Najitha Banu and Chimi Kinley
Department of Zoology, School of Bioengineering and Bioscience, Lovely Professional University, Phagwara144 411 (Punjab), India
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ABSTRACT
Diamondback moth, Plutella xylostella (L.) (Lepidoptera: Plutellidae), has become the most destructive insect pest of Brassicaceae plants globally. Numerous control methods are available to control the moth, such as host plant resistance, physical controls, chemical controls, cultural controls, and biological controls. The continued application of insecticides has led to the development of resistance to almost 97 chemical compounds. The biological methods also became inefficient in the control of the moth. Therefore, nanotechnology would provide green and efficient alternatives for controlling the pest without harming environment. This review focuses on control methods used to manage diamondback moth and nanomaterials’ potential in insect pest management as modern nanotechnology approaches. It focuses on the past, present, and future scope of diamondback moth management.

Keywords: Plutella xylostella, biological control, chemical control, silver nanoparticles, entomopathogenic fungi.

INTRODUCTION
Insects are the most ubiquitous, diverse among all organisms and are adaptable to the various types of habitat. Insects belong to the phylum Arthropoda and class Insecta. There are about 5.5 million insect species (Cardoso et al., 2020), with one million species found and described (Hotaling et al., 2020). Insects influence human cultures in numerous ways. They have been recognized worldwide as nutritious food containing the available essential protein, lipids, carbohydrate, high content of micronutrients, and some vitamins (Nowak et al., 2016; Pali-Schöll et al., 2019). The insects also positively affect the environment as they act as pollinators, weeds killer, soil builder, and natural enemies (Gavina et al., 2018). Insects such as Apis species (honey bees), Laccifer lacca, and Bombyx mori (silkworm) are commercially essential insects. They are known for the production of honey (Higes et al., 2011), lac (Yusuf et al., 2017), and silk, respectively (Rao et al., 2006).

Insects are considered pests if they compete for resources and transmit diseases to humans and the live-stocks causing damage to humans. Insect pests have a significant impact on an agricultural food product by damaging the crops. The crops are damaged by sucking, chewing, or boring and reducing the yield (Luo et al., 2012; Singh and Kaur, 2018). Agricultural insect pests are responsible for severe economic losses annually, costing farmers billions of dollars a year (Chattopadhyay et al., 2017) and threaten global food security (Pélissié et al., 2018). Insects are considered the major biotic factors that limit crop production (Bhat and Ahangar, 2018).

The major orders of insect pests are the Coleoptera (Wang et al., 2019), Lepidoptera (Qi et al., 2020) and Hemiptera (Wilson, 2019). These orders include pests such as Heliotherpa armigera, Aphids, Psyllids, Leafhoppers, Leptinotarsa decemlineata, Diabrotica virgifera, and Plutella xylostella. The order Lepidoptera is the second largest insect order that includes moths and butterflies. The larva of lepidopteran pest affects almost every crop (Rose and Singh, 2010). The diamondback moth, Plutella xylostella (L.) (Lepidoptera: Plutellidae), is a major cosmopolitan lepidopteran pest in the Brassicaceae family and is oligophagous (Farias et al., 2020) with Mediterranean origin (Huariptaand Sánchez, 2019). They are adaptable to adverse weather conditions and has an excellent ability to disperse with a short life cycle (Duarte et al., 2016). It also has a short generation time and a lack of effective natural enemies (Huariptaand Sánchez, 2019).

The larvae of diamondback moths have a chewing mouthpart (LI et al., 2018) and are voracious feeder that is continuously feeding on the leaves causing defoliation (Farias et al., 2020). It is projected that its annual management costs and associated crop losses are $4-5 billion globally (Shen et al., 2020). In Southeast Asia, Plutella xylostella outbreaks often cause crop losses of more than 90 percent (Marak et al., 2017).

It is very challenging to control diamondback moth by implementing effective and efficient management strategies. There are various methods for controlling the moth, such as physical, cultural, chemical, and biological methods. Physical and the cultural are the conventional method which is labor-intensive. When combined with other control methods such as biological control, cultural control reduces the P. xylostella populations. Still, the crops become susceptible, causing other pests attacks, leading to the overall yield loss (Philips et al., 2014). Chemical pesticides are generally used to control the diamondback moth. The continuous and incorrect
application of the insecticides has resulted in the resistance to such chemicals by the moth (Gupta et al., 2015). Chemical pesticides are toxic to the environment, have a negative impact on non-target insect species (El Husseini, 2019), and affect human health (Sonmez et al., 2017). Diamondback moth has developed resistance to several classes of conventional and novel insecticides (Xia et al., 2018). According to the Arthropod Pesticide Resistance Database (APRD), the moth is resistant to 97 chemical compounds and ranks first among the top 20 most resistant species (Shen et al., 2020). There was a need for alternate control, which is environmentally friendly.

The biological control is eco-friendly without harmful effects on human health and environment (Sonmez et al., 2017). The natural enemies are seasonal and difficult to rear. Entomopathogenic fungi are microorganisms controlling insects’ populations (Moorthi et al., 2015) and better alternatives for insecticides. The fungi have insecticidal properties and are rich sources of functional secondary metabolites (Ravindran et al., 2018). Several entomopathogens, like Beauveria bassiana, Metarhizium anisopliae, Isaria fumosorosea., Lecanicillium muscarium, are used to control agricultural insect pests (Duarte et al., 2016). The entomopathogens control of diamondback moth is a slow control with short shelf life and low host specificity (Philips et al., 2014).

Nanotechnology is an important field in science and engineering concerned with particle structure design, formulation, and manipulation. Nanotechnology provides alternate and promising management of insect pests to promote sustainable agriculture (Jampilek, and Kráľová, 2017). Nanoparticles are a large class of materials approximately 1-100 nm in size and have unique physical and chemical properties due to the high surface area and nanoscale size (Khan et al., 2019). Metallic nanoparticles have possible application in a diverse area such as electronics, coating, biotechnology, and agriculture. It can be synthesized through physical, chemical, and biological means. The biological synthesis of metallic nanoparticles is done using plants, algae, fungi, bacteria, and viruses which are low-cost, energy-efficient, and nontoxic (Thakkar et al., 2010). Silver nanoparticles synthesized through entomopathogenic fungi are more popular because they produce immense bioactive substances and are more suitable for producing nanoparticles on large-scale (Neethu et al., 2018).

The various strategies to control the diamondback moth infestation are reviewed. This review is mainly focused on the past, present, and future scope of the diamondback moth management, emphasizing the novel technology that is nanoparticles synthesis from the entomopathogens. It will also provide as a reference point to identify possibilities and potential research directions for nanotechnology in the control of diamondback moth.

**Population Ecology of Diamondback moth, *Plutella xylostella***

*Plutella xylostella* have originated from Europe and South Africa (Saeed et al., 2009) or have a Mediterranean origin (Wei et al., 2013). Since Brassica crops are originated in Europe and the diamondback moth feeding only on the Brassicaceae crops, it is accepted as European origin. It is also believed to be originated in South Africa based on the massive number of Brassica plants and parasitoids present (Kfir, 1998). Now, the diamondback moths are present worldwide and are reported in more than 128 countries (Venugopal et al., 2017). The widespread of DBM is due to its migrating capabilities. It occurs wherever the brassicas are grown and is the most distributed lepidopteran insects (Fu et al., 2014). The long-distance migration, overwintering population (Fu et al., 2014), environmental conditions, and natural enemies (Marchioroand Foerster, 2016) are responsible for the variation in its infestation level. The local population of the DBM increases when there are suitable hosts (Saeed et al., 2010). Diamondback moth overwinters as an adult in warmer climates (Philip et al., 2014).

It is an important pest of brassicaceous crops (Sithole et al., 2019). The moth can complete several generations in a year and it is reported differently in different region.

**Life Cycle of Diamondback moth**

The diamondback moth has a holometabolous development where complete metamorphosis occurs with four stages in its life cycle; adult, egg, larva, and pupa. The duration of each stage is dependent on temperature (Hermansson, 2016). Development of *P. xylostella* occurs between 8 and 32°C, at 14°C had seen the highest survival of the moth taking 41 days to complete one generation (Philip et al., 2014).

The adult is greyish-brown around 6-9 mm in length with pronounced antennae (Philip et al., 2014; Hermansson, 2016). Adult males and females live about 12 and 16 days, respectively, and females deposit eggs for about ten days. The mating occurs at dusk of the same day of emergence of the adult. DBM are weak fliers (Capinera, 2002) but can migrate long-distance using the air current (Marchioroand Foerster, 2016; Chapman et al., 2015).

Diamondback moth eggs are small, yellowish oval, and flattened, measuring 0.44 mm x 26 mm. They are deposited either singly or in small groups in depressions on the leaf surfaces or other parts. After mating, the female moth lay eggs around 11-188 eggs in 4 days of oviposition period (Capinera, 2002; Gautam et al., 2018). According to Philips et al., 2014 the female lay around 350 eggs in approximately ten days. The average period for egg development is 5.6 days (Gautam et al., 2018).

A fully grown diamondback moth larva is about 11.2 mm. The larvae have four instars and require about 5-7 days for each instar, thereby having a total larval development time of 20–28 days (Philips et al., 2014). Each instar rarely exceeds 1.7, 3.5, 7.0, and 11.2 mm, respectively (Gautam et al., 2018). The larval bodies are colorless in the first instar but change to green as it develops. Initially, the first
Critical review on past, present and future scope of diamondback moth management

Table 1: Generation time per year of diamondback moth in two regions.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Generation Time (per year)</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>Temperate region</td>
<td>4</td>
<td>Shakeel et al., 2017</td>
</tr>
<tr>
<td>Tropical region</td>
<td>3-4</td>
<td>Nguyen et al., 2014</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Nguyen et al., 2014</td>
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<td></td>
<td>20</td>
<td>Wainwright et al., 2020</td>
</tr>
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Table 2: List of some resistant insecticides of *Plutella xylostella*

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Insecticides</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>Spinosyns</td>
<td>Spinosads</td>
<td>Marak et al., 2017</td>
</tr>
<tr>
<td>Organophosphates</td>
<td>Phoxim</td>
<td>Shakeel et al., 2017</td>
</tr>
<tr>
<td>Pyrethroids</td>
<td>Cypermethrin</td>
<td>Zhang et al., 2016</td>
</tr>
<tr>
<td>Anthranilic diamides</td>
<td>Chlorantraniliprole</td>
<td>Wang et al., 2013</td>
</tr>
<tr>
<td>Phenylpyrazoles</td>
<td>Fipronil</td>
<td>Shakeel et al., 2017</td>
</tr>
<tr>
<td>Chlorfenapyr</td>
<td>Chlorfenapril</td>
<td>Xia et al., 2014</td>
</tr>
<tr>
<td>Diflubenzuron</td>
<td>Abamectin</td>
<td>Shakeel et al., 2017</td>
</tr>
<tr>
<td>Benzoylureas</td>
<td>Chlorfluazuron</td>
<td>Zhang et al., 2016</td>
</tr>
<tr>
<td>Avermectins</td>
<td>Difacectomycin</td>
<td>Zendal et al., 2017</td>
</tr>
<tr>
<td>Oxadiazines</td>
<td>Indoxacarb</td>
<td>Zhang et al., 2017</td>
</tr>
<tr>
<td>Novel</td>
<td>Pyridalyl</td>
<td>Wang et al., 2020</td>
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Table 3: Entomopathogenic fungi to diamondback moth

<table>
<thead>
<tr>
<th>Fungus</th>
<th>Crop</th>
<th>Virulence</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Beauveria bassiana</em></td>
<td>Cabbage (<em>Brassica oleracea var. capitata</em>), Canola (<em>Brassica napus</em>)</td>
<td>High</td>
<td>Agboyi et al., 2020; Sarfraz et al., 2006</td>
</tr>
<tr>
<td><em>Metarhizium anisopliae</em></td>
<td>Cabbage (<em>Brassica oleracea var. capitata</em>)</td>
<td>High</td>
<td>Zafar et al., 2020</td>
</tr>
<tr>
<td><em>Isaria fumosorosea,</em></td>
<td>Laboratory</td>
<td>High</td>
<td>Xu et al., 2017</td>
</tr>
<tr>
<td><em>Leccanicillium muscarium</em></td>
<td>Cabbage (<em>B. oleracea var. capitata</em>)</td>
<td>Low</td>
<td>Duarte et al., 2016</td>
</tr>
<tr>
<td><em>Isaria sinclairii</em></td>
<td>Cabbage (<em>B. oleracea var. capitata</em>)</td>
<td>Low</td>
<td>Duarte et al., 2016</td>
</tr>
</tbody>
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Instar larvae’ feeding habit is leaf mining. After the first instar, the larvae emerge from their mines, molt beneath the leaf, and after that feed on the leaf’s lower surface. Their chewing results in irregular patches of damage and the upper leaf epidermis is often left intact (Capinera, 2002). After the fourth instar, the larva stops consuming foliage before entering the prepupal stage (Hermannsson, 2016). During the larval stages, they have high feeding rates that cause high yield loss (Peres et al., 2017).

Pupation occurs in a loose silk cocoon, usually formed on the host plant’s lower or outer leaves (Gowri and Manimegalai, 2016). Pupae changes as they develop and have 7 to 9 mm in length, with the duration of the cocoon averages about 8.5 days that require 5-15 days to completely develop (Capinera, 2002). Abiotic and the biotic factors have significant influence in the DBM population (Farias et al., 2020).

Effect of biotic factor on DBM

The biotic factor includes natural enemies, crop species, and the plant’s age (Marchioro and Foerster, 2016). The natural enemies are predators and parasitoids (Sarfraz et al., 2005). These includes *Diadeyma semiclausum* (Tonnang et al., 2010), *Apanteles piceo trichosus*, *Diadegma leontiniae*, *Cotesia plutellae*, *Siphona* (Marchioro and Foerster, 2016), *Microplitis plutellae*, *Diadegna insulare*, *Diadromus subtilicornis* (Philips et al., 2014), *Brachymeria citrae* and *Oomyzus sokolowskii* (Sow et al., 2012). More than 135 species of parasitoids attacking *P. xylostella* have been reported from various parts of the world (Syed et al., 2018).

The main factor affecting *P. xylostella* population dynamics was parasitism, leading to 48 percent of the difference in the abundance of pests (Marchioro and Foerster, 2016). The larval parasitoid’s parasitism rate of DBM larvae was higher than that of pupal parasitoid (Gautam et al., 2018). Many agricultural systems have unsuitable environments for natural enemies due to high levels of disturbance. The impact of parasitoids on the diamondback moth populations was low and inefficient in controlling the population.
moth. Parasitoids are particularly susceptible to chemical insecticides (Sow et al., 2013). Pesticides used against *P. xylostella* constitute a significant cause of the reduction in larval parasitoid populations (Marchioro and Foerster, 2016).

### Effect of abiotic factor on DBM

DBM is the terrestrial ectothermic organism with extensive thermal tolerance (Garrad et al., 2015). Temperature, relative humidity, and rainfall conditions may benefit or disturb pests’ infestation (Farias et al., 2020).

The temperature has a significant effect on the growth, survival, reproduction and migration of DBM (Golizadeh et al., 2007; Xing et al., 2019). *P. xylostella* could not develop from egg to adult outside 8-32°C temperature when reared at a constant temperature. However, some individual stages have complete development outside this temperature range. Moreover, different life stages have different temperature limits for the complete development, with the later instars providing the widest ranges (Liu et al., 2002).

Diamondback moth infestation occurs around December, January and reaches a peak in March (Bhagat et al., 2018). The moth performs much better at high temperatures because of its rapid development rate, consequently short mean generation time and high fecundity, in contrast with low temperatures. In a wide temperature range (10-30 °C), *P. xylostella* can grow and reproduce, and considerably affects the moth’s biological characteristics (Golizadeh et al., 2009). High temperatures and humidity are limiting conditions for the insect (Farias et al., 2020).

### Outbreaks of Diamondback moth

DBM outbreaks are sporadic and often present throughout the growing season, and infestation may change from endemic to epidemic (Ahmed et al., 2009). The major causes of the moth outbreaks in different countries are insecticide resistance and the lack of effective natural enemies. In California, a single outbreak of DBM caused the losses more than in excess of US$6 million (Shelton et al., 2002; Philips et al., 2014). It was reported that outbreaks of *P. xylostella* in Southeast Asia and Uttar Pradesh, India, caused more than 90% and 100% of crop losses respectively (Marak et al., 2017; Sharma et al., 2017). The moth is now distributed globally, causing crop damage, and has a management cost of more than 1 billion USD annually (Silva and Furlong, 2012).

### Host Plant Interaction

*P. xylostella* are oligophagous insects that use closely related host plants for oviposition and feeding. The larvae feed on Brassicaceae crops including cabbage, broccoli, cauliflower, and canola (Wainwright et al., 2020; Miluch et al., 2013). *P. xylostella* ’s host plant is confined to Brassicaceae and the moth is attracted by plants’ chemical or physical stimuli. The brassica plants have certain glucosinolates, cardenolides, plant volatiles and waxes (Sarfraz et al., 2006; Golizadeh et al., 2007). Glucosinolates, a class of protective chemicals, do not defend against DBM attack, but serve as effective feeding and oviposition stimulants. Furlong et al., (2008) reported that the enzyme glucosinolate sulfatase in the gut of DBM break glucocinaltes and the DBM is not affected by the level of brassica glucosinate.

The moths show a powerful arrest response by staying or hopping to adjacent plants after their host plant is identified. The initiation of reproductive activities of DBM is stimulated by signals from the host plant. The calling behavior in DBM is increased when the host plant is present. The host cue accelerates egg maturation, increases mating and shortens the time required between adult and the oviposition onset (Sarfraz et al., 2006). DBM performance on particular hosts that can also be influenced by ecological factors. High-density populations can display a broader host breadth than low-density populations. The age of the host plant also affects the DBM populations (Furlong et al., 2008).

### Host Plant Resistance

Brassicaceae crops differ in susceptibility to *P. xylostella*’s damage. Mustards, turnips, and kohlrabi are among the most DBM resistant crops (Capinera, 2002). Host plant characteristics, biochemical, or morphological factors may promote resistance to the diamondback moth (Philips et al., 2014). Some components in the host has been identified to show resistance to the DBM like glucocheirolin, glucorucin, glucorinni, glucotropaeolin, allyl isothiocyanate, gluconapin, gluconasturtiin, progoitrin, sinalbin and sinigrin (Lim, 1990). Variations in plant morphological features, including leaf wax content, leaf color, or head compactness and plant biochemical compounds such as glucosinolates, may be involved in the differences in resistance (Philips et al., 2014).

Due to excess amounts of glucosinolate in the moth larval gut, the high total glucosinolates in the host do not harm DBM. A high level of myosinase in host plants leads to a decrease in the feeding activities of DBM (Sarfraz et al., 2006).

The glossy phenotype with dark and green leaves is found more preferred for oviposition by the diamondback moth than the waxy phenotype (Sarfraz et al., 2006). Ulmer et al., reported that Brassicaceae plants with glossy leaf wax show resistance to diamondback moth, causing the larva to spend more time in searching and less in feeding (Philips et al., 2014). So, surface waxes are also one of the significant parts of host plant resistance to DBM.

### Management of Diamondback moth

*P. xylostella* is the globally significant destructive pest attacking Brassicaceae crops (Venugopal et al., 2017). The pest’s common control is still the frequent use of insecticides despite the resistance shown. Other management options are physical, cultural, and biological control to suppress pest populations (Gurr et al., 2018). It is particularly challenging to control diamondback moth by implementing efficient and effective control approaches.

### Cultural Control
Cultural control makes the environment unfavorable to the pests to reduce the risk of pest damage and give the basis for integrated pest management in crops (Glen, 2000). It plays a vital role in managing diamondback moth that includes intercropping, crop rotation, and trap crops (Philips et al., 2014).

**Trap Cropping**

Trap crops are an older cultural method used to attract pests and, once in place, are treated with insecticides or managed within the trap crop (Satpathy et al., 2010). Badenes-Perez et al., (2004) assessed and recommended potential trap crops for the diamondback moth through a study conducted in 2002 and 2003. These includes glossy, waxy collards (Brassica oleracea L. variety acephala), Indian mustard (Brassica juncea L.) and yellow rocket (Barbarea vulgaris variety arcuata). When diamondback moth was with multiple hosts simultaneously, the number of eggs laid was more significant in these trap crops than the brassica cash crops (Badenes-Perez et al., 2004). Lu and his team conducted a study where the diamondback moth was given the choice of plants, Barbarea vulgaris, and Brassica campestris. It was concluded that the adult moth laid nearly all the eggs in B. vulgaris proving its great potential as a trap crop for the management of the moth (Lu et al., 2004). The trap crop strategy had shown some success in reducing the diamondback moth’s economic injury level in brassica crops (Philips et al., 2014).

**Crop Rotation**

The Diamondback moth has a narrow host range, so crop rotation proved to be an effective method for controlling the moth by disrupting the life cycle (Sayyed et al., 2002). Crop rotations to non-Brassica and clean cultivation practices are one of the control tactics for P. xylostella. Continuous planting of the same Brassicaceae crops increases the DBM populations. It was reported that rotating crops reduces the moth population significantly due to disrupting the availability of the host (Sorensen et al., 2016; Shakeel et al., 2017). This approach is not possible for the commercial vegetable producing sector because of demand and high cost (Philips et al., 2014).

**Intercropping**

Intercropping plants function as a natural barrier by interrupting the interaction between pest and host plants (Sayyed et al., 2002). Intercropping of brassica with the other non-host crops is one of the cultural management tactics to control P.xylostella.

It was found that intercropping cabbage with tomato, chilli, onion, pepper, garlic, dill and clover can repel diamondback moth. So, intercropping could replace the insecticides in controlling DBM (Yarou et al., 2017; Asare-Bediako et al., 2010) and can significantly reduce pest populations but are not universally useful (Philips et al., 2014).

**Physical Control**

Physical control reduces the DBM populations using tools that physically affect pests and their physical environment. It alters the physical environment of the moth reducing the threat to the crops. The control methods affect the pest’s physiological and behavioral processes, giving immediate control of the insect pest (Sorensen et al., 2016). Li et al.,(2016) found that a high-voltage-bicycle-powered device draws and eliminates adult DBM.

The blue-light traps and fine-mesh netting houses were also found capable of controlling adult DBM. In Thailand, the combination of yellow sticky traps with other conventional methods were reported effective against diamondback moth(Lim, 1990).

**Chemical Control**

Chemical control is one of the main DBM management tactics globally. A wide range of insecticides are available and its applications control the diamondback moth populations. Insecticides like Spinosad, Indoxacarb, Chlorantraniliprole, Emamectin benzoate, Chlorfenapyr, Fipronil, Flubeniamide, Acephate, Pyridalyl, Cyantraniliprole, Difenthiuron, Fenvalerate, and Novaluron were used earlier for the control (Gautam et al., 2018). Fenvalerate, followed by lufenuron, was the best treatment against P. xylostella, followed by novaluran and chlorfenapyr (Sharma et al., 2017).

**Insecticides Resistance**

The most significant problem in DBM management is the development of insecticidal resistance. Due to irrational application, it has developed resistance to insecticides reducing its effectiveness and became the most difficult pest to control. It is also due to the moth having many generations per year, which increases resistance (Venugopal et al., 2017; Gautam et al., 2018; Hermansson, 2016). The first insecticide reported to show resistance by the diamondback moth is DDT in 1953 in Lembang, Indonesia (Sayyed et al., 2002). Now, Shen et al., (2020) reported that DBM has developed resistance to 97 active compounds, ranking it first among the 20 most resistant species. It was found that the interaction between gut microbiota and the insect immune system results in enhanced chemical insecticide resistance (Xia et al., 2018).

P. xylostella developed resistance to the basic insecticide classes such as organochlorides, organophosphates, synthetic pyrethroids, and carbamates (Mahmoudvand et al., 2011). Diamondback moth resistance were also found against many insecticides such as abamectin, chlorantraniliprole, cyantraniliprole, flubeniamide, betacypermethrin, Spinosad, fipronil, phoxim, chlorfenapyr, and chlorfluazuron (Chen et al., 2010; Shakeel et al., 2017). A higher degree of resistance was also reported in cypermethrin, decamethrin, and quinalphos (Gautam et al., 2018).

**Biological Control**

Biological control is an environmentally friendly control which involves natural enemies like parasitoids, predators, and pathogens without any adverse effect on human (Sonmez et al., 2017; Sayyed et al., 2002). The natural enemies attack all life stages of diamondback moth.
reducing the pest population (Philips et al., 2014). They are seasonal and difficult to rear (Moorhiet et al., 2015) and better alternatives for insecticides. Diamondback moth has various natural enemies, including fungi, bacteria, viruses, predators, and parasitoids (Kuchár et al., 2019).

**Natural enemies**

Predators are recognized to cause pest populations’ mortality and are considered an essential factor in managing insect pests (Shakeel et al., 2017). Numerous studies have been done to understand the role of predation in diamondback moth larvae. Different predators, such as Syrphids, Hemerobid, Staphylinids, Vespids, Chrysopids, Anthocorids, and carabid beetles were reported (Sayyed et al., 2002; Philips et al., 2014). Euborellia annulipes were also found to have a predatory role in controlling the DBM (Nunes, 2018). However, predators are not useful on a large scale. Though they are natural enemies, there is little information about predators’ feeding habits in the natural habitat (Hosseini et al., 2012).

Parasitoids parasitize and kills the egg, larvae, larval-pupae, and pupae of the DBM (Haverkamp and Smid, 2020; Furlong et al., 2008). Numerous parasitoids are essential in controlling diamondback moth, and over 130 species are reported, attacking different moth life stages (Baharet et al., 2014). Parasitoids such as Trichogramma and Trichogramma toidea (Hymenoptera:Trichogramma tidae) parasitize P. xylostella eggs (Navik et al., 2019), but most parasitoids attack larvae and pupae of diamondback moth (Furlong et al., 2008). Navik et al. (2019) has found that integration of Trichogramma chilonis and Bacillus thuringiensis managed the DBM efficiently with maximum yield. Larval parasitoids are the most dominant with high control potential, which includes major Hymenoptera genera Diadegma (Ichneumonidae), Microplitis (Braconidae), Cotesia (Braconidae), and Oomyzus sokolowski (Munire et al., 2015; Capinera, 2002). Parasitoids like Pteromalus, D. collaris, and D. subtilicornis were found to parasitize diamondback moth pupae (Shakeel et al., 2017). The parasitoids are highly sensitive to insecticides, therefore need a proper selection of insecticides to maintain parasitoids (Philips et al., 2014).

**Entomopathogens**

Several entomopathogens, including viruses, fungi, bacteria, and nematodes have been used for the control of P. xylostella due to resistance shown by the moth. The bacterium, Bacillus thuringiensis was able to manage the diamondback moth in the past but now found to be ineffective to the bacteria (Naviket et al., 2019; Mahar et al., 2004).

**Entomopathogenic fungi**

Entomopathogenic fungi plays a dynamic role in insect population in the ecosystem (Mainaet al., 2018). Several entomopathogenic fungi like Beauveria bassiana, Metarhizium anisopliae, Isaria fumosorosea, Isaria sinclairii, and Lecanicillium muscarium are useful in controlling diamondback moth. The entomopathogens control of diamondback moth is slow with short shelf life and low host specificity (Philips et al., 2014). B. bassiana and M. anisopliae are the most common commercial biopesticides due to being target specific, persistence in nature and easy mass production (Godonouet et al., 2009). A study done in 2007 concluded that Metarhizium anisopliae isolates (M.a(OM3-STO) and M.a(OM1-R)) and B. bassiana isolate (B.b(OM2-SDO) were effective in controlling the diamondback moth (Loc and Chi, 2007).

**Beauveria bassiana** strain MG-Bb-1 (10' conidia/ml) were tested against DBM larvae and found more than 95 percent DBM mortalities (Masuda, 2000). Duarte et al. (2016) has reported that entomopathogenic fungi when used along the compatible chemicals were very effective. When second instar DBM larvae were treated with Beauveria bassiana with concentration 10' conidia/ml, it was observed that the mortality rate was between 94 and 100% (Duarte et al., 2016).

**Nanotechnology**

Nanotechnology is a promising interdisciplinary research area opening up broad opportunities in various fields like agriculture, medicine, pharmaceuticals, and electronics (Rai and Ingle, 2012). The nanoparticles are a large class of material having size approximately between 1 to 100 nm (Huanget al., 2015). Nanoparticles are categorized according to their properties, sizes, and shapes. The various classes are metal nanoparticles, carbon-based NPs, fullerenes, ceramic NPs and polymer NPs (Khan et al., 2019). It has unique physical and chemical properties which is due to their nanoscale size, shape, high surface area, conductivity and have been applied in various fields like drug-gene delivery, antimicrobial agents, biological sensor, bioremediation, etc. (Huanget al., 2015; Tyagi et al., 2019). It can be used in agricultural tools in the form of nanopesticides, nanofertilizers, and nanosensors (Yasurand Rani, 2015; Chhipa, 2019).

**Nanoparticles as nanopesticides**

Nanopesticides is a recent development in the field of agriculture which offers a range of advantages: increased durability, efficiency and the reduction of amount of active ingredient (Kookana et al., 2014). The application of nanomaterials can develop efficient methods for pest control (Rai and Ingle, 2012). Several nanoparticles like silver, copper, gold, nano silica, zincoxide, titanium dioxide and aluminium oxide nanoemulsion has proved its insecticidal properties against many different insect pests (Chhipa, 2019).

The nanosilica’s effect has been evaluated on DBM larvae in a laboratory using dust spray, larva dipping, leaf dipping, and solution spray methods. It was reported that dust treatment was most effective than the other treatments in controlling the moth and the morality rate increased up to 58% and 85 % at 24 and 72 h after treatment, respectively (Shoaib et al., 2018). The nano-silica gets absorbed into the cuticular lipids by physisorption, causing
the pest’s death (Rai and Ingle, 2012). Preetha et al., (2018) reported that the when Titanium dioxide nano particles (TiO₂) were used, a mortality of DBM was more than 50 per cent on seventh day indicating that nano material as the alternate insecticides.

Metal nanoparticles were synthesized using physical, chemical, and biological methods. The physical methods have low efficiency while the chemical methods have adverse biological risks and harmful environmental consequences due to their toxicity (Elamawiet al., 2018). These methods are toxic, costly, and not eco-friendly (Rafique et al., 2017). So, efforts were made for the green synthesis of metal nanoparticles, mainly the silver nanoparticles, for the control of the harmful pest species (Athanassiouet al., 2018).

Compared to other methods, green synthesis is regarded as cost-effective, safe, sustainable, and environment-friendly. It also possesses a broad variability of metabolites that may aid in the reduction and a single-step method for biosynthesis process (Govindarajan et al., 2016). Devi et al., (2014) stated that all larval instars and pupae of the cotton bollworm, Helicoverpa armigera, (Lepidoptera: Noctuidae), were susceptible to AgNPs synthesized by leaf aqueous extract of Euphorbia hirta (Malpighiales: Euphorbiaceae). Similarly, larvae of the mosquitoes C. quinquefasciatus and A. subpictus exposed to AgNPs synthesized from the leaf aqueous extract of Mimosa pudica (Fabales: Fabaceae) were also found to be lethal (Marimuthu et al., 2011). Suresh et al., (2014) observed that AgNPs exposed 100% mortality of second-instar larvae of A. aegypti (Diptera: Culicidae). Dinesh et al., (2015) conducted the field experiment and reported that AgNPs synthesized by leaf aqueous extract of Aloe vera were toxic for all larvae instars of A. stephensi.

Among various management methods, synthesis of nanoparticles through the entomopathogens method was proven to be most efficient in control strategies. It is environmentally friendly and can be synthesized on a large scale (Tyagi et al., 2019). AgNPShas been synthesized through a green method, which is an inexpensive process by using entomopathogenic fungi like Beauveria bassiana, Isaria fumosorosea, as well as the endophytic bacteria like Pennisetum setaceum and Bacillus megaterium (Banu and Balasubramanian, 2014; Banu and Balasubramanian, 2015; Ahmed et al., 2019). Entomopathogenic fungi were found to be more attractive agents for silver nanoparticle synthesis because they were easily managed and offer excellent metals tolerance. They also secrete huge amounts of extracellular proteins that provide the stability of the nanoparticles (Guilger-Casagrande and de Lima, 2019). Soni and Prakash (2012) reported that fungus Aspergillus niger has been selected for the synthesis of gold nanoparticles (AuNPs) and it was found to be more effective against the C. quinquefasciatus larvae than the A. stephensi and A. aegypti larvae. KHOOSHE-BAST et al., (2016) stated that the mortality rates obtained from the test conducted on T. vaporariorum with ZnO NPs and fungi (Beauveria bassiana) at the highest concentration were 91.6 % and 88.8 %, respectively. Therefore, entomopathogen synthesized nanoparticles can be used in the insect pest control and has a great scope in the diamondback moth management.

CONCLUSION

Plutella xylostella is a significant pest in Brassicaceae crops, and its control is necessary. There are many strategies for controlling moth, such as physical, chemical, cultural, and biological control. Diamondback moth has developed resistance to over 97 insecticides due to the overuse of chemicals. Biological control also has become ineffective against the moth. So, there is a need for novel technology for the management of the cosmopolitan diamondback moth.

The development of novel technologies is essential in the growth of agriculture. Nanotechnology can provide a novel solution for the management of diamondback moth, developing a reliable and eco-friendly process for synthesizing metallic nanoparticles. Nanoparticles have a pesticidal property, which can be an alternative solution for insecticide resistance. There are various scopes whereby nanoparticles can be synthesized from different agents like entomopathogens to control the Brassicaceae crops’ major pest, diamondback moth. Synthesizing of nanoparticles has become one of the most promising new approaches for pest control in the present.

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