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

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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 andAhangar, 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 *Helicoverpa 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 (Huaripataand 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 (Huaripataand 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 (Jampílek, 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

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

Regions	Generation Time (per year)	References
Temperate region	4	Shakeel *et al.,* 2017
	3-4	Nguyen *et al.,* 2014
Tropical region	14	Nguyen *et al.,* 2014
	20	Wainwright *et al.,* 2020

Table 2: List of some resistant insecticides of *Plutella xylostella*

Chemical class	Insecticides	References
Spinosyns	Spinosads	Marak *et al.,* 2017
Organophosphates	Phoxim	Shakeel *et al.,* 2017
	Quinalphos	Gautam *et al.,* 2018
Pyrethroids	Cypermethrin	Zhang *et al.,* 2016
Anthranilic diamides	Chlorantraniliprole	Wang *et al.,* 2013
Phenylpyrazoles	Fipronil	Shakeel *et al.,* 2017
Chlorfenapyr	Chlorfenapyr	Xia *et al.,* 2014
Diafenthiuron	Diafenthiuron	Shakeel *et al.,* 2017
Benzoylureas	Chlorfluazuron	Zhang *et al.,* 2016
Avermectins	Abamectin	Shakeel *et al.,* 2017
Oxadiazines	Indoxacarb	Zhang *et al.,* 2017
Novel	Pyridalyl	Wang *et al.,* 2020

Table 3. Entomopathogenic fungi to diamondback moth

Fungus	Crop	Virulence	References
Beauveria bassiana	Cabbage (*Brassica oleraceavar. capitata*), Canola (*Brassica napus*)	High	Agboyi *et al.,* 2020; Sarfraz *et al.,* 2006
Metarhizium anisopliae	Cabbage (*Brassica oleracea var. capitata*)	High	Zafar *et al.,* 2020
Isaria fumosorosea,	Laboratory	High	Xu *et al.,* 2017
Lecanicillium muscarium	Cabbage (*B. oleracea var. capitata*)	Low	Duarte *et al.,* 2016
Isaria sinclairii	Cabbage (*B. oleracea var. capitata*)	Low	Duarte *et al.,* 2016

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 (Hermansson, 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 (Marchioroand Foerster, 2016). The natural enemies are predators and parasitoids (Sarfraz *et al.,* 2005). These includes *Diadeyma semiclausum* (Tonnang *et al.,* 2010), *Apantelespiceo trichosus*, *Diadegma leontiniae, Cotesia plutellae, Siphona* (Marchioroand Foerster, 2016), *Microplitis plutellae*, *Diadegm ainsul* are*, 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 (Marchioroand 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 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 (Marchioroand 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, andconsiderably 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. Thelarvae 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 glucocinolates and the DBM is not affected by the level of brassica glucosinolate.

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, glucoerucin, gluconringiin, 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 glusosinolate 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 makesthe 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 *arcuate*. 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, Flubendiamide, Acephate, Pyridalyl, Cyantraniliprole, Diafenthiuron, 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 reported against many insecticides such as abamectin, chlorantraniliprole, cyantraniliprole, flubendiamide, beta-cypermethrin, 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 (Moorthi*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 had been done to understand the role of predation in diamondback moth larvae. Different predators, such as Syrphids, Hemerobiid, 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 parasitizes 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 (Bahar*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* (Munir*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, *Bacillusthuringiensis*was able to manage the diamondback moth in the past but now found to be ineffective to the bacteria(Navik*et al.,* 2019; Mahar *et al.,* 2004).

Entomopathogenic fungi

Entomopathogenic fungi plays a dynamic role in insect population in the ecosystem (Maina*et 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 (Godonou*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 (10^7conida/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 10^7 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 (Raiand Ingle, 2012).The nanoparticlesare a large class of material having size approximately between 1 to 100 nm (Huang*et 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. (Huang*et 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 (TiO_2) 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 (Elamawi*et 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 (Athanassiou*et 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 armiger*, (Lepidoptera: Noctuidae), were susceptibile 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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