Biopesticides: Current Status and Future Prospects in India

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Abstract

For over a century, chemical control of pests is a common practice in agriculture. The average reduction in global crop loss due to use of pesticides is around ~39%. The postharvest losses and quality decline caused by storage pests are major problems in a subtropical country like India. So, the farmers have relied heavily on the use of chemical pesticides to improve their crop production, which is now paying a huge toll on the human health and environment. Though the chemical pesticides are very effective, what concerns over their use is their effect on soil and environment and presence of residue in food products. Another major issue is the development of resistance in the pests. Therefore, the use of biopesticides to control pests is now preferred over synthetic pesticides because of their pest control ability and diverse mode of actions which helps in avoiding resistance development in the pests. In a country like India with a huge diversity of plants, there is an urgent need for identifying new biopesticides which can serve the purpose of pest control. India needs to develop its own biocontrol agents (BCA) because it will be cost-effective and also environment-friendly. Major hurdle in the development and use of new biopesticides in India is the commercialization process. The farmers are reluctant to use the new products because of high cost and no practical knowledge.

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6.1 Introduction

Indian agriculture sector accounts for 18% of India's gross domestic product (GDP), and about 58% population of India is dependent upon agriculture for its livelihood. India has the tenth largest arable land resources in the world and is among the 15 leading exporters of agricultural products in the world. Agricultural exports from India reached USD 38.21 billion in FY18 and USD 21.61 billion between April and October 2018.The food grain production during 2017–2018 was estimated at record 284.83 million tonnes, and the government is targeting to increase it to 285.2 million tonnes in 2018–2019. The gross value added by agriculture, forestry and fishing is estimated at Rs. 17.67 trillion (USD 274.23 billion) in FY18. The above data clearly depicts the reliance of Indian economy over agriculture. The Indian government is aiming to double the farm income by 2022. Impetus to this daunting task of doubling the farmers' income can be provided only by increasing investments in agricultural infrastructure such as irrigation facilities, warehousing and cold storage and by using genetically modified crops (APEDA, Union Budget 2018–2019). Innovative solutions are required to meet the ever-increasing demands for food and fibre by fast-growing population of India. These demands can only be met by protecting crops from pest losses while conserving limited natural resources and maintaining quality of the environment (Naranjo et al. 2015). Usage of biopesticides has seen rise in recent years, and according to a data presented by the Union Ministry of Agriculture, between 2010–2011 and 2016–2017, the all-India consumption of biopesticides increased from 5151 to 6340 tonnes (by 23%), while that of chemical pesticides grew from 55,540 to 57,000 tonnes (only 2%) for the period under review.

In the early periods of the nineteenth century, Agostine Bassi was the first one to use spores of the white muscardine fungus (*Beauveria bassiana*) to protect silkworms from insect pests and diseases (Xiao et al. 2012). But till date, the biopesticide market has not evolved as per the expectations, and its market is still very restricted when compared to synthetic pesticides. The use of biopesticides to control pests is preferred over synthetic pesticides just because of their mode of action. On one hand, where synthetic insecticides are neurotoxic to pests, biopesticides perform their action by inducing mating disruption, anti-feeding, suffocation and desiccation of the pests. Unlike chemical pesticides, which are made from industrial chemicals, biopesticides are derived from plant extracts, fungi, bacteria, protozoans and minerals. They are used for crop protection and are found to be benign for both humans and the environment (Olson 2015). In the presently followed pest control strategy, the biopesticides have grown importance over the conventional synthetic pesticides. Biopesticides have become popular because of the variety of mode of actions they offer; hence, resistance development in pests is slower (Bisen et al. 2015; Fraceto et al. 2018; Ram et al. 2018; Singh et al. 2017). Therefore, there is substantial scope in identifying and developing biopesticides as alternative pest management resource (Rajapakse 2016). To feed the ever-growing population of India, more crop production is required in the limited amount of land which is available for cultivation. To support the fast-growing population of the nation, along with a high emphasis on achieving food grain self-sufficiency, Indian farmers were compelled to make considerable use of pesticides. Undoubtedly, the use of chemical pesticides has provided a valuable aid to agricultural production, increasing crop protection and yield, but their uncontrolled use has traded heavily on the environment. The overall benefit derived from the pesticides has been overshadowed by the discovery of pesticide residues in various dimensions of the environment (Yadav et al. 2015). Their nontarget effects on beneficial microbes are critical for soil health; their residues are left in feed and fodder and also cause environmental pollution (Singh et al. 2015).

The average production loss due to pests in India has been reported to be as high as USD 42.66 million (Subash et al. 2017). Very few chemical pesticides are available in the Indian pesticide market. This is because some products have been withdrawn from the market for regulatory or commercial reasons or due to the development of resistance by the pests against these products. So, there is an urgent need to look for some better technologies and products based on biological processes to control the pests (Kumar 2012). Biopesticides have been found to be the most suitable candidate for this purpose, but in a developing nation like India, there are several hurdles in the path of commercializing biopesticides. Major constraint being the slow action and low persistence of biopesticides when exposed to solar UV, high cost of production and lack of awareness among the Indian farmers. Apart from this, the poor awareness of decision-makers about opportunities offered by biopesticides, lack of multidisciplinary expertise in the crucial later stages of development, difficulty in conducting toxicological tests and the long testing period of bioactive compounds before registration and commercialization are the other challenges that need basic attention (Keswani 2015a, b; Keswani et al. 2016).

According to a report, the pesticide consumption in India increased by almost 50% from 2009 to 2015. However, per hectare use of pesticide in India was 0.29 kg/ha in 2015 which was far less compared to other countries like China (13.06 kg/ha), Japan (11.85 kg/ha), Brazil (4.57 kg/ha) and other Latin American countries (Subash et al. 2017).

6.2 Classification of Biopesticides

The three different classes of biopesticides that the US Environmental Protection Agency (EPA) has identified are microbial, biochemical and plant-incorporated protectants (PIPs). In microbial pesticides, whole microorganism such as bacteria, fungi, viruses and others are used as pesticides as the active ingredient and have been used efficiently to control insect pests. Despite being specific for its target pest, each active microbial ingredient can check the growth of several different kinds of pests.

In biochemical pesticides, microbial extracts or natural products from other sources like plant extracts or yeast fermentation products are used. These pesticides perform their action by nontoxic mechanisms. The biochemical pesticides often include the following: (a) semiochemicals (hormone mimics), insect sex pheromones that interfere with their mating and population build-up; (b) hormones, moult hormones (ecdysteroids) and juvenile hormones (IGR); (c) natural plant regulators, auxins, gibberellins, cytokinins and inhibitors; and (d) scented extracts (attractants) that are very small molecules and are used as traps and vegetable oil (Rajapakse 2016).

Plant-incorporated protectants (PIPs) are those substances that are produced naturally in genetically modified (GM) crops and are typically macromolecular in nature (Parker and Sander 2017). Such examples of producing transgenic plants may include incorporation of Bt gene, kinase inhibitor gene, lectins, chitinase, etc. into the plant genome. No harmful effect on either humans or animals is observed by the protein products which are produced by these transgenic plants to develop resistance against the pests (Kumar 2012).

All the prototype biopesticides have evolved from the bacteria *Bacillus thuringiensis* (Bt) that produce a toxin (Bt toxin) which binds to insect gut receptor protein and disrupt the gut upon ingestion. All the three varieties of biopesticides (microbial, biochemical and PIP varieties) are derived from this bacteria and its toxin.

6.3 Growth Drivers for India Biopesticide Market

The Indian agriculture has seen a sharp increase in the use of chemical pesticides in the last few years posing serious implications on human health, environment and groundwater. Hence, it has become imperative to find an environment-friendly substitute for the chemical pesticides. Biopesticides have been seen as next generation pesticides and are also believed to have a huge potential to promote sustainable agriculture in this country. On account of presence of higher pesticide residues in food crops and increasing pest resistance, strict regulations have been imposed on use and sale of synthetic pesticides by some developed countries. Around 500 biopesticides, duly registered by the Central Insecticide Board (CIB), are available in the Indian market. The efficacies of these products have been demonstrated in many laboratories, but the major problem is their quality control. The factors driving the growth of the Indian biopesticide market are the environment-friendly nature of biopesticides, encouraging public support policies, increasing public awareness and lesser development of pest resistance.

6.3.1 Government Efforts to Promote Use of Biopesticides

In India, the pesticides are used as the most important tool to protect public health and help in agricultural development. However, the overuse of pesticides is now showing the reverse effect. Pesticides constitute an integral part of the present-day agriculture, but there are some serious problems which are associated with it and these problems must be tackled with strong policies. There are several government agencies which regulate the use of pesticides taking into consideration their residues in food and water (Yadav et al. 2015). According to an annual global report, there are three million cases of acute, severe poisoning which occur due to intoxication of pesticides (Gunnell and Eddleston 2003; WHO 1990). It is a significant health issue in India as well, but the government has till date failed to produce any national data for it.

However, the Government of India (GOI) has shown its concerns about the ill-effects of pesticide use on human health by implementing measures, such as integrated pest management (IPM), prohibition of highly hazardous pesticides, restricting the use of toxic compounds and the development of a National Implementation Plan (NIP). In addition, the use of biopesticides has been strongly recommended by the National Farmer Policy. IPM, which is an eco-friendly approach to manage pests, has been used by GOI to strengthen and modernize pest management approaches. In IPM, various cultural, mechanical and biological methods and need-based use of chemical pesticides, preferably biopesticides and biocontrol agents (BCA), are employed. The 31 central IPM centres operating across the nation perform the tasks of monitoring the pests and diseases, production and release of biocontrol agents and biopesticides and conservation of biocontrol agents apart from providing training to farmers at the basic level (Yadav et al. 2015).

The health risks associated with persistent organic pesticides has greatly perturbed international community. All the nations are now seeking mutual help in order to reduce and minimise the production, use and release of persistent organic pesticides. India has also signed and ratified three international legally binding instruments out of six which have been negotiated and concluded till date. India signed the Stockholm Convention on Persistent Organic Pollutants (SCPOPs), which is one of the most important legally binding international agreements to protect human health and the environment from some of the most dangerous chemical on earth on 14 May 2002, which was later ratified on 13 January 2006.

Being a member nation of SCPOPs, India had to develop a National Implementation Plan (NIP) which recommends certain priorities to the government in order to ensure the implementation of the obligations of the convention. Some of the recommendations of NIP for the GOI include the following: to encourage and develop nonpersistent organic pesticide alternatives to DDT, encouragement for production and demonstration of neem-based biopesticides, designing distinct mechanism to deal with new persistent organic pesticides and strengthening of institutions involved in pesticides research and capacity building.

The manufacturing, sale, transport and distribution, export, import and use of pesticides are regulated by the Ministry of Agriculture through the ‘Insecticides Act 1968’. The central and state governments are assisted on technical matters by Central Insecticide Board and Registration Committee of India (CIB&RC). The data for all kinds of pesticides are collected by CIBRC.

6.3.2 Biopesticides in Integrated Pest Management

One of the biggest growth drivers of biopesticides in the pesticide market is their suitability in integrated pest management (IPM) programs, in combination with other biological, cultural and pesticide approaches. Some advantages of using biopesticide are that they are less toxic to pollinators and are compatible with natural enemies such as hymenopteran parasitoids. Also, in addition, they help in delaying pest resistance when used in rotation with synthetic pesticides (Birch et al. 2011). The biopesticides are now being made more efficient by combining them with 'soft' biological options. For example, the biopesticides which are used for controlling codling moth are based on a granulosis virus and have been available for many years but because of their poor performance were not in use but became highly useful on integration with a codling moth female sex pheromone to disrupt mating and thus helping in control (Krawczyk et al. 2010).

6.3.3 Increased Health Awareness

Exposure of humans to the pesticides present in the environment can be through different routes such as by inhalation, ingestion or dermal contact. The effects of pesticide poisoning are sometimes devastating. Several diseases like cancer, kidney failure, immunosuppression, sterility, etc. are attributed to pesticide poisoning. During the last two decades, public concern over pesticides' adverse effect has been clearly visible. After successful implementation of green revolution, India is now facing another bigger challenge of conserving its ecosystem from the toxic chemical pesticides (Abhilash and Singh 2009). The people have now become more health conscious, and now the demand for organic products are on rise in the Indian market.

6.4 Market of Biopesticides in India

Presently, biopesticides encompasses a minor portion of entire crop fortification market which accounts for 5% in total and is supposed to contribute up to 50% of the overall pesticide market by 2050 (Parker and Sander 2017). Presently, the estimated global market of biopesticides is of ~USD 3–4 billion which corresponds to compound annual growth rate (CAGR) of 14.1%. The Indian biopesticide market is also growing rapidly and is centred across a few companies which dominate the organised sector of the Indian biopesticide market. Pest Control India, International Panaacea Ltd., T Stanes and Biotech International are the major organized players (Table 6.1). Other companies dominating Indian market for their products, services and continuous product developments are Camson Bio Technologies Ltd., Sri Biotech Laboratories India Ltd., Valent Biosciences Corp., Eid Parry, etc.

The major share of the Indian biopesticide market is contributed by these few companies because of their sustained R&D procedures and deep-rooted distribution

Table 6.1 List of some Indian biopesticide companies and their products

S. No.	Company name	Product name	Properties	Reference
1.	Pest Control India	Niprot®	Controls the soil-borne fungal pathogen and protects the crops against root and collar rot. It also protects the plants against damping off and root-knot nematode and uses formulation of antagonistic fungi	https://www.pestcontrolindia.com
		Su-Mona®	Controls and tackles soil-borne pathogens affecting horticulture crops and is also effective against bacterial root knot and lesion nematodes. It increases systemic resistance and also plant growth	
		Bio-Jaal™	It is the first oil-based biopesticide in India, enhances field stability, adheres on insect body in a better way and kills the pathogen at low exposure. It does not affect beneficial insect	
2.	Biotech International Ltd.	Biolep	Contains strain of *Bacillus thuringiensis* var. *kurstaki,* serotype H-3 a, 3b, strain Z-52. Available in wettable powder form. Highly active up to 3rd instar larva of insect. It does not harm human beings, animals, fishes, birds, etc	https://www.biotech-int.com/biosepticides.html
		Bioline/Verti-Star	Contain strain of *Verticillium lecanii.* It is highly active on sucking pests like scale insects, *Coccus viridis*, aphids, thrips, mealybugs, jassids, hoppers, etc. on crops like mustard, sugarcane, mango, sorghum, rice, cotton, tomato, grapes, pomegranates, etc. infects all stages of insects including eggs, larvae, pupae, nymphs and adults and is safe for environment, and human beings	
		Biomet/Ankush	Contains strain of *Metarhizium anisopliae.* Available in wettable powder form and aqueous suspension. Highly active on white grubs, beetle grubs, caterpillars, semiloopers, cutworms and sucking pests. It infects all stages of insects including eggs, larvae, pupae, nymphs and adults. The spores attach to insect cuticle/integuments; they germinate and penetrate insect body	

(continued)

Table 6.1 (continued)

S. No.	Company name	Product name	Properties	Reference
		Biorin/Kargar	Contains strain of *Beauveria bassiana*. Available in wettable powder form as well as aqueous suspension. It is highly active on lepidopteran caterpillars including *Helicoverpa, Spodoptera, Plutella*, borers, hairy caterpillars, pests of vegetables and fruit plants and sucking pests like scale insect, mealy bug, etc.	
		Biovirus-H	Contains strain of nuclear polyhedrosis virus (NPV) of *Helicoverpa armigera*. Available in aqueous suspension. Highly active on *Helicoverpa armigera* pest of cotton, pigeon pea, gram, tomato, okra, brinjal, chilli, cabbage, pea, groundnut, tobacco, millets, oilseed crops, roses etc.	
		Biovirus-S	Contains strain of nuclear polyhedrosis virus (NPV) of *Spodoptera litura*. Available in aqueous suspension. Highly active on *Spodoptera litura* pest of cotton, groundnut, pulses, cabbage, chillies, tobacco, oil seeds crops, roses, etc.	
3.	International Panaacea Ltd.	Milgo™ (fungicide)	Contain *Ampelomyces quisqualis,* it controls the powdery mildew and is also effective against *Botrytis cinerea, Alternaria solani, Colletotrichum, Coccodes, Cladosporium cucumerinum*, etc. at early growth stage of pathogens. The target crops include cucurbits, grapes, apple, peas, beans, tomato, pulses, cumin, chillies, coriander, mango, ber, peas, strawberry, medicinal and aromatic crops and roses that are infected by powdery mildew	https://www.iplbiologicals.com
		Varunastra™, Vertifire-L (insecticide)	It contains *Verticillium lecanii* and infects all the stages of insects. Aphids, thrips, mealybugs, white flies and all types of mites are its target insects. The target crops include banana, grapes, guava, citrus, mango, sapota, apple, coconut, paddy, cotton, tomato, chilly, brinjal, onion, okra, tea, cardamom, coffee, aromatic and medicinal crops	
		Nematofree (Nematocide)	It effectively controls plant parasitic nematodes specifically root-knot nematodes infecting tomato, brinjal, carrot and okra crop. It is effective against nematode (*Meloidogyne* spp.), reniform nematode (*Rotylenchulus* spp.) etc.	
		Suraksha™ (growth promoter)	It contains product of *Rhizobacteria* and enhances the growth of crop plants like grapes, banana, pomegranate, guava, mango, citrus, chilly, tomato, brinjal, okra, tea, coffee, plantation crop, medicinal and aromatic crops, cotton, maize, paddy, wheat, etc.	

4.	T. Stanes	Bio-Nematon	Bio-Nematon contains spores and mycelial fragments of a selective strain of naturally occurring entomopathogenic fungus *Paecilomyces lilacinus*. The spore of this fungus acts by infecting, parasitizing and killing eggs, juveniles and young adults of most phytophagous nematode species. It is compatible with neem and other biopesticide products	http://www.tstanes.com
		Nimbecidine EC	It is a neem oil-based botanical insecticide containing azadirachtin and other limonoids including meliantriol, salannin, nimbin and various other terpenoids. It controls pests such as whitefly, aphids, thrips, mealybugs, caterpillars and leafhoppers in a wide range of crops. It exhibits its mode of action by acting as an antifeedant, repellent, oviposition deterrent, insect growth regulator and sterilant	
		Bio-Power	Bio-Power contains spores and mycelial fragments of a selective strain of naturally occurring entomopathogenic fungus *Beauveria bassiana*. It is a biological insecticide; it effectively controls pests such as borers, cutworms, root grubs, leafhoppers. Whitefly, aphids, thrips and mealybug. It increases the productivity by improving the crop health and is eco-friendly	
5.	Fortune Biotech	Fortune Aza	It is a 3% azadirachtin-formulated insect growth regulator (IGR). It controls more than 300 species of insect and prevents moulting between larval, pupal and nymphal stages	http://www.fortunebiotech.com/products.php
		Fortune Aza Technical	Most potent tetranortriterpenoid isolated till date from neem seeds. It is effective against more than 300 insect species as antifeedant, repellent and as an insect growth regulator. It provides a broad-spectrum pest control for fruits, vegetables and plantation crops, greenhouses, turf, outdoor ornamentals and agricultural crops such as sugarcane, paddy, cotton and tea. It is stable at cool temperature in the absence of water and light and also stable in organic solvents	
		Fortuneem Cake	It controls nematode population and other soil-borne diseases and is rich in NPK and micronutrients. It controls nematode population by increasing the metabolism of microbes, which proves to be toxic for the nematodes	

(continued)

Table 6.1 (continued)

S. No.	Company name	Product name	Properties	Reference
6.	Excel Crop Care	Sudocel	Sudocel contains a prominent soil-inhabiting bacterium *Pseudomonas fluorescence*. The bacterium acts as an excellent bioagent by coiling around and penetrating and killing fungi that are pathogenic to crops. They also secrete enzymes and antibiotics which can digest their cell walls	http://www.excelcropcare.com/product
		Tricho HR	It contains a beneficial fungi *Trichoderma harzianum* 1% and is highly effective in controlling wide range of soil-borne crop diseases. It is biodegradable and target specific and leaves no toxic residues	

channel spread across several regions of India. Due to their sincere efforts, the consumption of biopesticides increased from 219 tonnes in 1996–1997 to 683 tonnes in 2015–2016 (Subash et al. 2017). The pace of development of Indian biopesticide market is not very impressive. Its market can be only expanded with government's aid not only in monetary terms but also by the development of storage facilities at different level of supply chain, which require special training and skills.

6.5 Analysis of Indian Biopesticide Industry

While considering legislative bodies governing biopesticide industries in India, two critical apprehensions should be taken into account. Firstly, guidelines must be coherent to guarantee human and environmental safety and, secondly, to illustrate constant and dependable quality of biopesticide products (Chandler et al. 2011). According to (Chandler et al. 2011), only sanctioned biopesticide products can be legally used for crop protection in most of the developed and developing countries. In India, production of biopesticides is principally structured by legal agendas originally considered for chemical pesticides and insecticides. The Insecticides Act, 1968, and Insecticides Rules, 1971, legalize import, registration process, manufacture, sale, transport, circulation and utilization of insecticides with a view to overcome risk to human beings and animals, as well as all connected matters (Abhilash and Singh 2009) (Fig. 6.1).

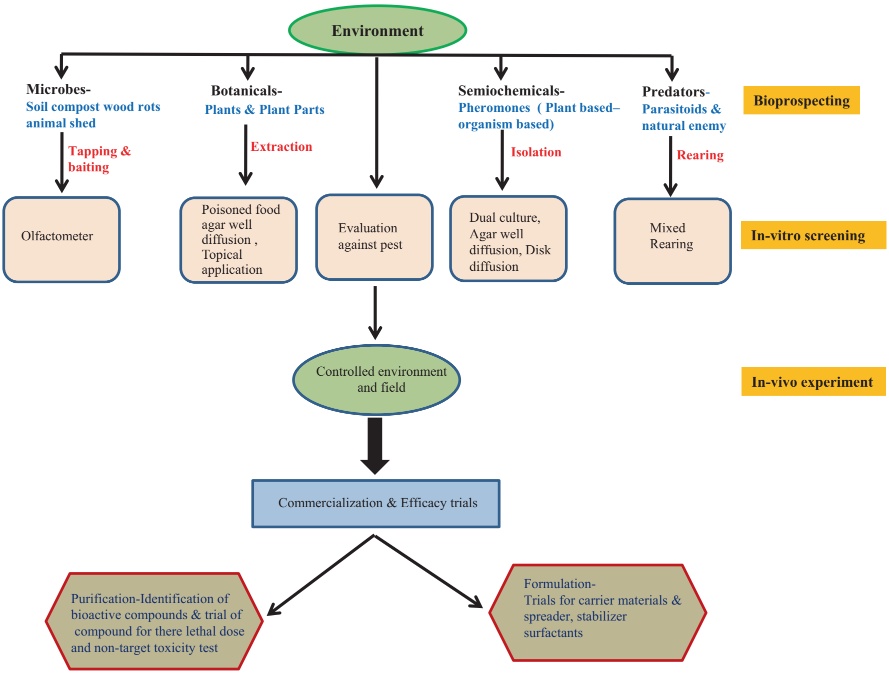

Fig. 6.1 Steps in production and commercialization of different types of biopesticides

Pesticide industry in India has been largely divided into six groups comprising herbicides, insecticides, fungicides, plant growth regulators, biopesticides and rodenticides (Bharatbhai 2017). There is an enormous prospective of development of biopesticide market in India in future years depending on the government support and increasing consciousness on the use of nontoxic and environmental friendly pesticide in country. The Indian biopesticide market has witnessed an unexpected growth in FY 2007–2012 in which western and southern regions of India have been a major sink where biopesticides are chiefly expended. The biopesticide market has observed a growth and revenue contribution of 26.4% compared to 10.2% growth recorded in total pesticide market during the same period. So far, more than 500 types of biopesticides are available in the Indian market, which are suitably registered by the Central Insecticide Board (CIB). Widespread research on these biopesticides in national laboratories has confirmed the effectiveness of these biopesticides (Singh et al. 2016), but maintaining their quality requires considerable R&D approach which is a monotonous assignment and not all the companies are efficient towards this technology (Table 6.2). Furthermore, their high prices have restricted their consumption by poor Indian farmers which demote the superiority of these pesticides in Indian market.

6.6 Comparison of Indian and Global Biopesticide Market

According to an estimate, there will be around nine billion people on the globe by 2050. In order to increase agriculture yield, pesticides are used, and their present estimated market value is of USD 50–60 billion. The global pesticide use has increased by 50-fold in the last 70 years (Vendan 2016). The average reduction in global crop loss due to use of pesticides is around ~39% (Oerke 2006). The current global biopesticide market is approx. 6% of the total pesticide market and is estimated to be of ~USD 3–4 billion. The compound annual growth rate (CAGR) of biopesticides is 14.1% which is relatively higher compared to CAGR of synthetic pesticide (4.8%).

The Indian population is expected to exceed 1.5 billion by 2050. There will be a huge pressure on the agricultural sector to feed such a gigantic population by increasing food production in an environmentally sustainable manner. To achieve this objective, use of pesticides is preferred in Indian agricultural system. India is not only among the biggest consumers of pesticides, but also it ranks 12th in production of it. Vendan (2016) reported that per hectare consumption of pesticides is 280 g/ha in India, but an interesting thing is that per hectare consumption of chemical pesticides is significantly low compared to global data. Of the total pesticides consumed in India, insecticides contribute to more than 50%, while herbicides' and fungicides' share are low. Due to limited number of chemical pesticides available in the Indian market and also because of development of pest resistance and health hazards associated with synthetic pesticides, the demand for biopesticides has been growing in India as well. According to a report of the Department of Agriculture Cooperation and Ministry of Agriculture and Farmers Welfare, the consumption of

Table 6.2 Indigenous biopesticides (list of representative biopesticides registered in India under section 9 (3) of the Insecticides Act, 1968)

Biopesticides	Taxus	Formulations	Targets	Trade name
Bacillus thuringiensis subsp. *israelensis*	Bacterium	5.0% WP, 5.0% AS	Lepidopteran pests	Tacibio
B. thuringiensis subsp. *Kurstaki*		5.0% WP, 7.5% WP	Lepidopteran pests	Bio Dart
Pseudomonas fluorescens		0.5%, 1.0% WP	Soil-borne diseases	Bio Dart
Bacillus subtilis		2.0% AS		
Bacillus thuringiensis subsp. *sphaericus*		1.3% FC	Mosquito larvae	VectoLex
Bacillus thuringiensis subsp. *galleriae*		1.3% FC		
Trichoderma viride	Fungus	1.0% WP	Soil-borne pathogens	Bioderma
Beauveria bassiana		2.15% WP, 10% SC or 1.0%, 1.15%	Coffee berry borer, diamondback moth, grasshoppers, whiteflies, aphids	Myco-Jaal
Ampelomyces quisqualis		2.0% WP	Powdery mildew	Bio-Dewcon
Trichoderma harzianum		0.5%, 1.0%, 2.0% WP	Soil-borne pathogens	Biozim
Metarhizium anisopliae		1.0%, 1.5% WP	Coleoptera, Lepidoptera, termites, mosquitoes, leafhoppers, beetles, grubs	Biomet
Paecilomyces lilacinus		1.0%	Whitefly	Yorker
Verticillium lecanii		1.15%	Whitefly, coffee green bug, homopteran pests	Verisoft
Verticillium Chlamydosporium		1.0% WP	Nematodes	
Nuclear polyhedrosis virus of *Helicoverpa armigera*	Virus	0.43%, 0.5%, 0.64%, 2.0%	*Helicoverpa armigera*	Helicide
Nuclear polyhedrosis virus of *Spodoptera litura*		0.5%, 2.0%	*Spodoptera litura*	Spodocide

Source: Ministry of Agriculture and Farmers Welfare, Government of India
Note: WP wettable powder, *AS* aqueous solution or aqueous suspension, *SC* suspension concentrate, *FC* flowable concentrate

biopesticides has increased from 219 tonnes in 1996–1997 to 683 tonnes in 2000–2001 and further to around 3000 tonnes in 2015–2016. In 2016, the Indian biopesticide market was USD 70.45 million, and it is growing with a CAGR of 17.08% (https://www.mordorintelligence.com/industry-reports/indian-biopesticides-market).

6.7 Biopesticide Commercialization and Regulatory Barrier

Of the overall pesticide market in India, biopesticides constitute around 3% only. Till date, only 14 biopesticides have been registered under the Insecticide Act 1968 in India (Subash 2017). According to a forecast, the 5-year compound annual growth rate of Indian biopesticide industry will be of 17.08% between 2017 and 2022 (https://www.mordorintelligence.com/industry-reports/indian-biopesticides-market). However, the overreliance of Indian farmers on synthetic chemical pesticides can be removed only by substantial increment of biopesticide industry. Many factors that have been hampering the potential growth of biopesticides in the Indian market are their unavailability, lesser reach and also continued disappearance of mixed/multiple cropping system. Development of new biopesticides is difficult because of the several features of the agricultural sectors. The farmers find it hard to use new products because they compare the cost involved and the profit earned in exactly the same manner as the companies which will develop any biopesticide product only if it earns a good profit:

Lack of profit from niche market products – a lot of biopesticides are highly selective like the bioinsecticides based on baculoviruses, such as the CpGV. They are typically selective against a particular insect; thus, they have low profit potential as the size of their market is limited.

Fixed costs – the farmers who use biopesticides face a large fixed cost compared to other farmers who use conventional chemical pesticides because the fixed cost associated with biopesticides is not distributed among a large number of farmers, and hence early users find it disadvantageous.

Farmers risk aversion – A large number of farmers who have been using chemical pesticides for a very long time have gained substantial experience and confidence in their effectiveness, while there are a lot of uncertainties in farmers' mind when it comes to using new products for which they don't have even practical knowledge.

On the basis of several characteristics of the living and nonliving entities that make up the biopesticides, every government tries to regulate their authorization and use. These regulations are meant for human and environmental safety and also to ensure that reliable biopesticide products enter into the market. In EU, only those biopesticides are used for crop protection whose efficacy has been quantified and proved and the guidance of OECD in this respect is even more strict; only those biopesticide that gets authorization pose minimal or zero risk. The major hurdles in the path of commercialization of new biopesticides are the regulatory authorities who sometimes don't have enough expertise in biopesticides, and they tend to delay in the process of authorization. In addition, another obstacle is that the regulatory system for biopesticides is based on chemical pesticide model. Several of the government regulators have been treating the biopesticides in the same manner as chemical pesticides and are thus slow in recognizing the fact that for biopesticides a separate regulatory process is needed (Chandler et al. 2011).

Even if India has a great diversity of botanicals, the commercialization of botanical pesticides is difficult here due to quality control and product standardization issues. Like synthetic pesticides, the improper and excessive use of botanical pesticides leads to development of pest resistance. The phytotoxicity of botanical pesticide is also a matter of concern. For example, neem oil-based biopesticide is often phytotoxic to tomato, brinjal and ornamental plants at high levels (Nawaz 2016).

6.8 Pest Management Strategies

6.8.1 Microbial Biopesticides

Microbial biopesticides are also known as biological control agents (BCAs). In this category of pesticide, the active component is a microorganism that is naturally occurring or genetically modified bacteria, fungi, algae, viruses or protozoans. The advantages of microbial pesticide are their higher selectivity and less or no toxicity in comparison with conventional chemical pesticides present in market (MacGregor 2006). The commonly used microbial biopesticides are living organisms which are pathogenic or toxic for the target pest. They broadly include biofungicides (*Trichoderma, Pseudomonas, Bacillus*), bioherbicides (*Phytophthora*) and bioinsecticides (Bt) (Gupta and Dikshit 2010). Microbial pesticides contain a variety of microorganisms of different genera and species of bacterium, fungus, virus, protozoan or alga, rickettsia, mycoplasma and nematodes. They dismantle, kill or inhibit their target pests either by producing toxic metabolites or by causing diseases that leads to death of the pest. They also prevent their target pest by establishment of other microorganisms through competition or various other modes of action (Clemson 2007). Microbial biopesticides may be delivered to crops in many forms including live organisms, dead organisms or spores (Fig. 6.2).

Out of the total global biopesticide present in market for all crop types, the contribution of bacterial biopesticides is about 74%, fungal biopesticides 10%, viral biopesticides 5%, predator biopesticides 8% and other biopesticides 3% (Mishra 2015). By 2008, there were approximately 73 microbial active ingredients that were registered by the USEPA.

6.8.1.1 Bacterial

Bacteria are prokaryotic, unicellular organism of varying length and shape. The maximum number of the insect pathogenic bacteria belongs to the families of *Bacillaceae*, *Pseudomonadaceae*, *Enterobacteriaceae*, *Streptococcaceae* and

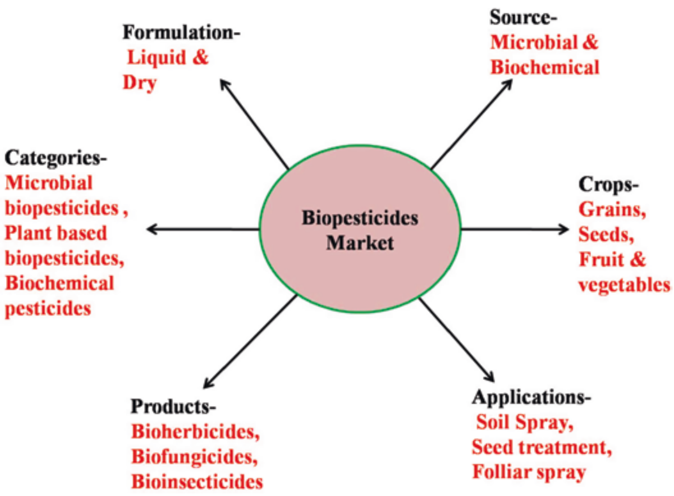

Fig. 6.2 Types of biopesticide market on the basis of their origin and application

Table 6.3 Bacterial species used as biopesticide

Bt variety	Target pest	References
Serratia entomophila	Grass grub	Johnson (2001)
B. thuringiensis subsp. *Israelensis*	Mosquito and blackflies	Kabaluk (2010)
B. thuringiensis subsp. *Kurstaki*	Lepidopteran larvae	
B. thuringiensis subsp. *Galleriae*	Colorado potato beetle	
Lysinibacillus sphaericus	Mosquito larvae	Berry (2012)
Bacillus moritai	*Diptera*	Kunimi (2007)
Burkholderia spp.	Chewing and sucking insects and mites; nematodes	Ruiu (2018)
Saccharopolyspora spinose	Insects	

Micrococcaceae (Kachhawa 2017). Among all types of biopesticides, the most common is bacterial pesticides. The major volume of commercially produced microbial control agent are bacteria, including both gram-positive, spore-forming *B. thuringiensis* and *Lysinibacillus sphaericus*, and gram-negative, non-spore-forming *Serratia entomophila*. According to the most recent data, *Chromobacterium subtsugae and B. thuringiensis* subspecies are the most commonly used microbial pesticides at global level (Glare et al. 2012; Lacey et al. 2015). The major species of *B. thuringiensis* species are used for suppression of different types of lepidopteran pests, forest pests, mosquitoes and black flies (Table 6.3). The insecticidal activity of *B. thuringiensis* and *L. sphaericus* is mainly due to protein toxins (δ endotoxins or Cry proteins) within parasporal inclusions, which must be ingested to become larvicidal. This endotoxin is soluble in the high pH of the stomach and is cleaved to the toxic moieties by gut proteolytic enzymes. These toxins bind to the receptors and create pores on enterocytes followed by osmotic imbalance resulting in cell rupture, compromising integrity of the gut epithelium. Invasion of the main body cavity and subsequent septicemia caused by gut-resident bacteria leads to death of the target pest (Lacey et al. 2015). Due to their high specificity and safety in the environment, *B. thuringiensis* and Cry proteins are efficient, safe and sustainable alternatives to chemical pesticides for the control of insect pests. Bt has been widely used to control insect pests important in agriculture, forestry and medicine.

6.8.1.2 Viral

Like bacteria and fungi, the entomogenous viruses also play a significant role in crop protection. These viruses are host-specific, infecting only one or a few closely related species; thus, the nontargeted insects are not infected by them. A US-based company, Omnilytics, has developed different types and variety of phage products used for the control of *Xanthomonas campestris* pv. *vesicatoria* and *P. syringae* pv. *tomato* for the treatment of a disease mainly caused in tomatoes [bacterial spot and bacterial speck on tomatoes] (Frampton et al. 2012). Among the insect viruses found in nature, those belonging to the baculoviruses family (*Baculoviridae*) were considered for the development of most commercial viral biopesticides (Kachhawa 2017). Baculoviruses are particularly attractive for use as biopesticides due to their high host specificity. They have been shown to have no negative impacts on plants, mammals, birds, fish, or nontarget insects (D'Amico 2007). Baculoviruses are host-specific, rod-shaped enveloped viruses having circular, supercoiled double-stranded DNA (80–180 kbp), which are 230–385 nm in length and 40–60 nm in diameter (Rohrmann 2011). Around 600 baculoviruses have been isolated from *Lepidoptera* (butterflies and moths), *Hymenoptera* (sawflies) and *Diptera* (mosquitoes) (Biagini et al. 2011). These viruses are mainly used as phage pesticides, and they exhibit efficient horizontal transmission. When ingested by the host insect, infectious virus coat gets dissolved, and it is liberated internally and become active. The budded virus initiates infection to other tissues in the haemolymph, i.e. fat bodies, nerve cells, haemocytes, etc. The cell infected in the second round of virus replicate in the insect larva also produce budded virus but in addition occlude virus particles within polyhedral in the nucleus. The accumulation of polyhedral within the insect proceeds until the host consists almost entirely of a bag of virus. In the severe stage of infection, the insect liquefies and thus releases polyhedral, which can infect other insects upon ingestion. The infected larvae show symptoms of negative geotropism before succumbing to the virus infection, thereby facilitating widespread dissemination. Within a few days, the host larvae are unable to digest food and so weaken and die (Thakore 2006). Under favourable conditions, the virus kills the pest within a week (Kachhawa 2017).

6.8.1.3 Nematodes

Entomopathogenic nematodes are non-segmented, soft-bodied roundworms. The maximum members are obligate parasites, and some are facultative parasites of insects. The natural habitat of these nematodes are soil and recognize their specific host by means of carbon dioxide release, motion, vibration and other chemical substances secreted by the host (Kachhawa 2017). Heterorhabditidae and

Steinernematidae are the two families that have been effectively used as biopesticide (Jess et al. 2005). Entomopathogenic nematodes are considered as nontoxic to humans and as effective biopesticide because of host-specific characteristic. The adult nematodes are not free-living; only juvenile stage is free-living and infective to the host. Both family of nematodes *Heterorhabditis* and *Steinernema* are present in symbiotic association with bacterial species *Photorhabdus* and *Xenorhabdus*, respectively (Ferreira and Malan 2014). The immature juvenile stage release cells of their symbiotic bacteria from their intestines into the haemocoel. The bacteria multiply in the insect haemolymph, and the infected host usually dies within 24–48 h of infection. After the death of the host, nematodes continuously feed on the host body tissue and get mature. The progeny nematodes develop through four juvenile stages to the adult. Depending on the available resources, one or more generations may occur within the host dead body, and a large number of infective juveniles are often released into environment to infect other hosts and continue their life cycle (Kachhawa 2017). Some important nematodes used as biopesticides are shown in Table 6.4.

6.8.1.4 Protozoan

Entomopathogenic protozoans are extremely diverse group of organisms comprising almost 1000 protozoan species mainly attacking numerous insect species like grasshoppers and heliothine moths (Senthil-Nathan 2015) and are commonly

Table 6.4 Nematode strains used as biopesticide

Name of nematodes	Host	References
S. glaseri	White grubs (scarabs, especially Japanese beetle, *Popillia* sp.), banana root borer	Poinar and Grewal (2012)
S. kraussei	Black vine weevil, *Otiorhynchus sulcatus*	Ansari (2010)
S. carpocapsae	Turf grass pests – billbugs, cutworms, armyworms, sod webworms, chinch bugs, crane flies. Orchard pests, ornamental and vegetable pests – codling moth, banana moth, cranberry girdler, dogwood borer and other clearwing borer species, black vine weevil, peach tree borer, shore flies (*Scatella* spp.)	Cruz-Martínez (2017)
S. feltiae	Fungus gnats (*Bradysia* spp.), shore flies, western flower thrips	
S. riobrave	Citrus root weevils (*Diaprepes* spp.) mole crickets	Bender (2014)
H. bacteriophora	White grubs (scarabs), cutworms, black vine weevil, flea beetles, corn rootworm, citrus root weevils (*Diaprepes* spp.)	Goudarzi (2015)
H. indica	Fungus gnats, root mealybug, grubs	van Niekerk and Malan (2012)
H. marelatus	White grubs (scarabs), cutworms, black vine weevil	Miles (2012)
Phasmarhabditis hermaphrodita	Molluscs	Ruiu (2018)
Heterorhabditis downesi	Black vine weevil *Otiorhynchus sulcatus*	Williams (2013)

referred as microsporidians (Kachhawa 2017). Microsporidia such as *Nosema* spp. and *Vairimorpha necatrix* are generally host-specific and slow-acting, producing chronic infections with general weakening of the host. *Nosema pyrausta* generally infects European corn borer (Kachhawa 2017) and *Nosema locustae* infects the grasshoppers (Senthil-Nathan 2015). The biological activities of these protozoan species are complex. The spore formed by these protozoans is the infectious stage and has to be ingested by the insect host for pathogenicity. The spore germinates in the midgut and sporoplasm is released invading the target cells causing infection of the host. The infection results in reduced feeding, vigour, fecundity and longevity of the insect host as inundated applied microbial control agents. There are many benefits like persistence and recycling in host populations and their debilitating effect on reproduction and effect overall fitness of target insects. Naturally, parasitoids and insect predators commonly play role as vectors distributing the disease.

6.8.2 Botanical Biopesticides

Since ancient time, India is the richest source of different varieties and diversity of plant species. India possesses the largest diversity of plant species having 47,000 plant species and total 7–8% of the world (Ghosh 2017). Botanical pesticides are potential alternative sources over chemical pesticide and are not harmful to the environment and other nontargeted pests. It is also known as ‘phytochemical insecticides’ and ‘green chemical insecticides’. New bioactive chemicals are being isolated and characterized every day from different varieties of plant species; more than 6000 species of plants have been screened against various types of pests. There are approximately 1005 species of plants having insecticidal properties, 384 with antifeedant properties, 297 with repellent properties and 31 with growth inhibiting properties (Vendan 2016).

Botanical pesticides are made by using some parts, plant extract or whole plant. They have the ability of insect killing, sterilization, weed control and plant growth-regulating activities. The application of botanical pesticides for the crop and stored products’ protection from insect pests has been a part of traditional agriculture form many years. In insect pest management, a number of plant products derived from neem, custard apple, tobacco, pyrethrum, etc. have been used as effective and safer insecticides (Nawaz et al. 2016). Azadirachtin compounds derived from the neem tree is sold under various trade names and used for several food crops and ornamental plants for controlling whitefly, thrips, scale and other pests. It affects the reproductive and digestive process of target pests (Dutta 2015) and does not affect other biocontrol agents. Neem products are effective against more than 350 species of arthropods, 12 species of nematodes, 15 species of fungi, 3 viruses, 2 species of snails and 1 crustacean species (Kandpal 2014). Several components of its leaves and seeds show marked insect control potential, and due to their relative selectivity, neem products can be recommended for many programmes on crop pest management. The major advantages of neem products over conventional chemical pesticides are its biodegradable and nontoxic nature to nontarget organisms

Table 6.5 Some plant products used as biopesticides

Plant products use as biopesticide	Target pests	References
Linalool	Peach potato aphid (*Myzus persicae*)	Gabryś (2005)
Neem	A variety of sucking and chewing insect	Cloyd (2009)
Pyrethrins	Flowerbugs and lacewings	Pezzini and Koch (2015)
Rotenone	Leaf-feeding insects, such as aphids, certain beetles (asparagus beetle, bean leaf beetle, Colorado potato beetle, cucumber beetle, flea beetle, strawberry leaf beetle, and others) and caterpillars, as well as fleas and lice on animals	Nawaz et al. (2016)

Table 6.6 Potential biopesticides (from plant extract) used in India

Plant extract	Effective against (target pests)	References
Adathodakashayam and Pudhina kashayam	Leaf folder, bacterial leaf blight, *Helminthosporium* leaf spot	Chauhan (2018)
Thriphala kashayam	Bacterial leaf blight and *Helminthosporium* leaf spot,	
Cow's urine arkam and sweet flag arkam	Bacterial leaf blight, *Helminthosporium* leaf spot, vein clearing disease, fusarium wilt	Kandpal (2014)
Garlic arkam	Leaf folder, bacterial leaf blight, *Helminthosporium* leaf spot	
Neem seed extract (for all crops)	Leaf folder, aphids, jassids, fruit borer and stem borer	
Andrographis kashayam and Sida kashayam	Aphids and borers in brinjal, ladies finger	Balasubramaniam (2008)
Extract of the species *Clitoria ternatea* (butterfly pea)	*Helicoverpa* spp.	Damalas and Koutroubas (2018)
Stilbenes isolated from grapevine extracts	*S. littoralis*	Akacha (2017)

(Senthil-Nathan 2015). Some important botanical biopesticides are shown in Table 6.5 and Table 6.6.

6.8.3 Biofungicides

Every year, Indian agriculture faces a huge loss due to deteriorating pathogens and detrimental pests (Savary et al. 2012). Some of these pathogens are gradually acting, while others act recklessly on eating the crops whose symptoms are sometime not easily noticeable to unaided eye (Yang et al. 2017). The pathogen which illustrates graphical symptoms after their full puffed infection comprises fungus. Fungi causes blight disease, damping of roots and seedling and endorses tanning of soft tissues (Broders et al. 2007). Till now, humans have established diverse chemical compounds as fungicides like strobilurin, alkyl phosphonate and etridiazole to defend the plant from these damage and upsurge the agricultural efficiency, but massive use of these compounds ensued in its build-up in different trophic levels and divisions of ecosystem and lastly getting and depositing inside human body causing injurious and sometime incorrigible diseases (Borges et al. 2015). To avoid this deposition, a substitute method of exclusion of these fungi was revealed which can be used in gigantic amount without any damage to any organism of ecosystem comprising humans (Cuthbertson and Murchie 2010). These replacement technique elaborated use of biofungicides which were isolated using biological source and can be used on different isolates of pathogenic fungi to exterminate the infecting fungus at a bulky scale (Heydari and Pessarakli 2010). These biological preparations comprise biofungicides which are isolated from fungi like *Trichoderma harzianum, Bacillus subtilis* and *Gliocladium virens* (Abbey 2018). Irrespective of quality of biocontrol agent, the course involved in its development, formulation and its delivery to the target system also regulates its effectiveness in the challenging area.

A thought-provoking part of a biofungicide against *Botrytis cinerea* on the microorganisms involved in alcoholic fermentation and on the grape biofilm. The usefulness was confirmed in the grape vineyard with some yeast like *Candida sake* or any bacteria like *Bacillus subtilis* to diminish the grapevine disease. Some of the biofungicides used was found to be of great advantage equated to its chemical equivalents. Based on the above submission and its exploitation in numerous arenas studied by Kumar and Singh (2014), the mounting attention in biofungicides accompanying with the product includes the following: (a) they are fundamentally less toxic than conventionally used chemical pesticides; (b) biofungicides distress only the target organism in broad-spectrum chemical fungicides which disturb unrelated organisms like birds, other insects and mammals; (c) by using as a constituent of integrated pest management, these biofungicides significantly limit the use of conventional pesticides; and (d) low cost of biofungicides paralleled to their synthetic counterparts.

Trichoderma spp. is an additional biopesticide technology established in recent years and found to be an operative fungicide against soil-borne diseases (Sharma et al. 2014). *Trichoderma* safeguards plant from pathogens by augmenting plant growth and protection under certain circumstances and by parasitizing detrimental fungi around the rhizosphere (Mukherjee et al. 2012). They are competent to parasitize plant pathogenic fungi in soil and yield antibiotics and fungal cell wall mortifying enzymes. They also strive with soil-borne pathogens for carbon and nitrogen and able to encourage plant growth by improving production of auxin like compounds (Vinale et al. 2008). The product of *Trichoderma* spp. is applied on seed coatings before seeding to soil. This mode improves the nutrient absorption by seeds and also substitutes fertilizer constraint of plant by up to 50%. One-time application of this product is sufficient to curtail inhibiting off disease caused by *Pythium* spp., *Sclerotium rolfsii* and *Rhizocotina solani*. Presence of these fungi is also interrelated with amplified sprouting and endurance of seeds (Keswani et al. 2013, 2014).

It is noted that around 250,000 higher plant species existing on this earth that are reflected as a reservoir of bioactive compounds with uncountable uses, comprising their use as pharmaceuticals and fungicides (Rungsung et al. 2015). Out of various fungicides isolated from several sources and verified for its usefulness, thymol and carvacrol are established as an operative ingredient against harmful fungal species whose projected mechanism comprises disbanding of fungal cell wall and cell membranes (Nazzaro et al. 2017). These products are extremely dynamic against *Botryodiplodia theobromae* and *Colletotrichum acutatum* which are the contributing agents of stem-end rot and anthracnose. They are the main components of essential oils of *Laminaceae* members like oregano, thyme and savoury. These mediators cause modifications in accumulation and morphology of hyphae which settles in lessening of hyphal diameter and lysis of their walls (Soylu et al. 2007). They are reasonably vigorous than other biofungicides due to their hydrophobicity which consents them to pass through fungal cell membrane which further distresses pH homeostasis and equilibration of inorganic ions resulting in disorganized cell structure and lysis (Cristani et al. 2007).

Isothiocyanates resulting from glucosinolates in the plant cells of family Crucifereae are found to retain compelling antifungal activity (Dufour et al. 2015). These isothiocyantaes comprises allyl, ethyl, methyl and benzyl. They impede fungal cells which encompass enzymes countering with the disulphide bonds or thiocyanate anion ensuing in inactivation of sulfhydryl enzymes. Furthermore, they are also involved in disengagement of oxidative phosphorylation reactions (Calmes et al. 2015). Purified metabolic extract of carrots are also found to contain antifungal properties due to occurrence of dodecanoic acid and pentadonoic acids which is active against yeast *Candida lambica* ensuing in inhibition of sporulation (Martínez 2012).

6.8.4 Bioinsecticides

Bioinsecticides are naturally formed insecticides which are produced or secreted as a by-product of organisms such as nematodes, bacteria and plants (Gašić and Tanović 2013). Microorganisms and plants are supposed to be a chief basis of biopesticides due to existence of higher constituents of antimicrobial agents and bioactive compounds (Nefzi et al. 2016). Natural enemies that comprise predator, pathogen and some birds are also sometimes used as a form of bioinsecticide in controlling insect pests (Knutson and Ruberson 2005). Bioinsecticides are also accessible in the form of plant extracts or crucial oils. They are acquired from leaves, flower, roots, and bark which are fresh or dried in nature (Chougule and Andoji 2016). Bioinsecticides are also mined from microorganisms including bacteria, virus, fungi, nematode and protozoans. Around 100 bacteria have been recognized as insect pathogens among which *Bacillus thuringiensis* is found to be most powerful microbial control agent. About 1000 virus which are specific to insects like *Nuclear polyhedrosis virus* (NPV) has been isolated which are competent to infest around 525 types of insects worldwide (Koul 2011). There are certain constructive features of utilising microbial biopesticides as described by Jindal et al. (2013): (a) These are bioactive compounds which are normally nontoxic to nontarget organisms including humans. (b) They are able to show synergistic effect with synthetic chemical pesticides. (c) The deposits left after their use do not show any antagonistic effect on humans or any other animals. (d) They improve the count of advantageous soil microflora which in turn progresses plant growth.

Most of the fungi existing in nature are damaging to plant health by triggering serious disease, but certain groups of fungi like entomopathogenic fungi which are natural managers of insect population are active against diverse agricultural pests. They act by penetrating the insect cuticle and producing toxins inside haemolymph which circumvents immune response of insects (Hajek and Leger 1994). The use of a fungus *Metarhizium anisopliae* which are pathogenic towards *Aedes aegyptii* mosquitoes has also been testified and the consequences designated a deterioration in this mosquito species due to their augmented vulnerability towards infection from this entomopathogen (Scholte et al. 2007).

The first achievement of viral bioinsecticide as baculovirus into the environment also resulted in improved destruction of spruce sawfly *Diprion hercyniae* during World War II. NPVs are largest group of virus which are used as bioinsecticide which blights many species of insects belonging to *Lepidoptera*, *Hymenoptera*, *Diptera* and *Trichoptera*. Their genomes are composed of double-stranded circular DNA and are able to reproduce inside the nucleus of host cells (Rohrmann 2008). Bacterial bioinsecticides has been reflected as the inexpensive and extensively used approaches of insect management (Chattopadhyay et al. 2017). In this scheme, convinced species of bacteria are used for poisoning the insects, but genus *Bacillus* are most broadly used pesticides (Ruiu 2015). One of the *Bacillus* species, *Bacillus thuringiensis*, has established molecular mechanisms to harvest endotoxins which produce transmembrane pores in the walls of insect gut that results in cell lysis due to osmotic discrepancy (Roh et al. 2007). Certain reports recommend that *B. thuringiensis* necessitates participation of commensal gut bacteria of insects to be wholly pathogenic (Broderick et al. 2009). Utilization of these toxins encompasses integration of toxin producing genes into the plant genome which is expressed as inactivated cry protein in designated part of plant. These proteins are cleaved and activated inside the insect gut once it is ingested causing pore formation and cell lysis of insects (Palma et al. 2014). Some commonly used bioinsecticides are given in the Table 6.7.

Table 6.7 Commonly used bioinsecticides and their target insects

S. No.	Bioinsecticide	Target organism	References
1.	Azadirachtin	*Amrasca devastans, Myzus persicae, Sitobion avenae, Lipaphis erysimi*	Akbar (2010)
2.	Thymol	*Megalurothrips sjostedti, Eloidogyne incognita, Helicotylenchus dihystera, Pratylenchus brachyurus*	Pumnuan and Insung (2016)
3.	*Phytoseiulus* spp. (predator organism)	*Tetranychus urticae, Tetranychus evansi*	Wekesa (2007)
4.	*Neoseiulus* spp. (predator organism)	*Tetranychus urticae, Oligonychus perseae*	McMurtry (2015)
5.	Baculovirus	Insects of genera *Lepidoptera, Hymenoptera, Coleoptera, Diptera*	Herniou (2004)

Pheromones are chemical signals emanated by living organisms to interconnect organisms of opposite sex (Yew and Chung 2015). Most of them are discriminating and produce no toxic residues, and production costs are significantly lower than that of synthetic chemical pesticides (Hajek and Eilenberg 2018). Pheromones are also of major importance in pest management when used in combination with traps as ‘pheromone traps’ using ‘attract and kill’ technique. This technique is called as mating disruption and is found effective in regulating a number of pests (Campos and Phillips 2014). This method is found operative in interruption of grape moth, grapevine moth and codling moth.

Certain bioinsecticides are active at every stage, while some are effective at definite stages of pest life cycle to reduce their population below a threshold level (Singh et al. 2010). Some biopesticides have a superiority in application due to their change in modes of action which permits them to overcome resistance from conventional pesticides and their influence on nontarget organisms (Spence and Lewis 2010). Synthetic female pheromones are used as attractants for males into traps which is used for mating disruption (Samietz et al. 2012). It is of utmost importance in development of biopesticide to overcome the problem of low shelf life, improper formulation as well as economic feasibility (Chandler et al. 2011).

6.9 Prospects of Biopesticides and Plant Diseases in India

Management of pest in an eco-friendly is no more a dream. Biopesticides can now be produced using the tools of molecular biology, biotechnology and nanotechnology in crop plants itself in a sustainable manner. They have been viewed as a safer alternative to chemical pesticides for a very long time. Their branding or commercialization can be done only by cooperation of the public and private sectors. Discovery of new substances and extensive research on formulation and delivery can help facilitate the development, commercialization and consumption of biopesticides.

India is an agriculture-based economy as around 58% of its population depends upon agriculture for its livelihood. Thus, it is very right to say that still agriculture serves as the backbone of Indian economy. With such a huge population getting employment due to this sector and also 18% GDP being contributed by it, agriculture sector needs proper attention of the government. The pest management practice in India is very complicated as a large number of farmers, crops and pests are involved. To control the pests, insecticides, fungicides and herbicides are commonly used, and they all are synthetic in nature. However, the share of insecticides is the highest in total pesticide use in India. According to a report (2016–2017) of the Ministry of Chemicals and Fertilizers and the Government of India, pesticides contributed to 3% in cotton, 1.9% in paddy, further lower in wheat (0.7%) and 0.3% in sugarcane of the total cost of cultivation. Insecticides contribute maximum of all the pesticides produced in India, its share being 39% in 2016–2017. Mancozeb, 2-4-D, acephate and profenofos are the major pesticides produced in India. Mancozeb and acephate are also among the top 5 pesticides exported from India, while glyphosate and atrazine are the major pesticides imported from China.

The Indian pesticide industry is facing tough challenges, the major being the stringent global environmental laws, little attention on R&D by domestic manufacturers due to high costs, need for innovation and product diversification, lack of awareness about safe use of pesticides among farmers, long gestation period for new products and product quality assurance. Thus, these negative environmental externalities can only be ruled out by using biopesticides, which can play a pivotal role in moving the focus from chemical pesticides to reliable, sustainable and environment-friendly alternative. The speed of development of biopesticide industry in India is not very impressive; it contributes only 3% of the pesticide market in India.

Commercialization and availability of biopesticides in the Indian market can be facilitated not only by maintaining low cost to farmers but also by the regulations that help in speedy registration of low-risk compounds with provision of incentives under the insecticides act. More field research of the presently available biopesticides needs to be done along with that recombinant DNA technology can also be employed to enhance efficacy of biopesticides in different cropping systems, which in turn may lower the continuous search for new substances. Some nanotechnology like microencapsulation of the available biopesticides can also be done to improve their residual action and hence their field use (Damalas and Koutroubas 2018). Information about the genes from the microbes and crop plants can be exploited to isolate genes beneficial against a particular pest, and these genes can be utilised to control insect pests and diseases (Kumar 2015).

Not only from pests and weeds but plant diseases caused by various groups of plant pathogens are often a big challenge in agriculture in India. Currently, chemical pesticides are being used in India to control plant diseases caused by several pathogens. Since, the use of these synthetic pesticides can severely damage the environment, so the reduction or elimination of the pesticide is inevitable.

The goal of having a clean and safe environment can be achieved by using new tools that are based on biological control agents (BCAs) and natural antimicrobial chemicals for disease control. A lot of research laboratories in India are now focussing on identification of the microorganisms and antimicrobial botanicals which can either inhibit the growth or kill the plant pathogens. All the countries need to develop their own BCAs because of the imposition of several quarantine procedures by the other countries. The mode of action of each BCA is different in different condition, so the Indian scientist must focus on developing indigenous BCAs as foreign BCAs may not work in Indian climate efficiently.

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