Article

Biopesticides: Current status and future prospects

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Abstract
In developing countries, the agricultural sector is playing a significant role to enhance the economy. Pests cause significant damage to crop production. Globally, the human population is rapidly increasing. To fulfill the food security for the rapidly growing human population, there is a strict need for eco-friendly insect pest management in Indian agriculture to sustain the agricultural produce for future needs. The present paper highlights biopesticides' current status and importance in India's farm sector and worldwide. Chemical pesticides are commonly used to control pests, which cause harmful impacts on the environment and non-target living systems, including human beings. Biopesticides are natural and a better substitute for chemical pesticides and provide an alternative for crop protection worldwide. Exploring and building their natural biopesticide resources in crop protection can help sustain agriculture. The trend of biopesticides consumption in India has shown a drastic increase in use over time which stood at 8847 and 8645 metric tonnes in 2019-20 & 2020-2021, respectively. However, a few numbers of biopesticides are easily accessible in the market. In India, as compared to chemical pesticides, biopesticides production, utilisation, and consumption is much lower due to a lack of research advancements, innovation and policies. Thus, the present paper provides a baseline overview of biopesticides and their classifications, current status and prospects.

Keywords biopesticides; chemical pesticides; economy; eco-friendly; pest management.

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1 Introduction

Agriculture is an anthropogenic activity but adversely affected by various pests such as bacteria, fungi, insects, and weeds, leading to reduced crop yield and production quality (Kumar, 2012). Over the past 50 years, the most common method for pest control has been the extensive use of chemical pesticides (Peshin et al., 2009; Zhang et al., 2011; Peshin and Zhang, 2014; Zhang, 2018). These pesticides were adopted in the 1940s with the help of dichlorodiphenyltrichloroethane (DDT) followed by other organochlorines, organophosphate, and carbamate pesticides, respectively (Nicholson, 2007). After that, the Green Revolution technology of crop production increased food production in developing countries through intensive inputs like chemical fertilisers and pesticides. In the late 1960s, the first wave of the green revolution was started in India, and due to the green revolution, India became self-sufficient in wheat production in the late 1970s. The green revolution impact was confined to northern India. Almost all crops, including rice covered in the second wave of the green revolution. It enhanced rural income and rural property. The tolerance of the wheat to abiotic and biotic stresses has made it possible to double the food production worldwide (Bahadur et al., 2014; Maurya et al., 2014; Kumar et al., 2016; Kumar, 2018).

By using agrochemicals, agriculture productivity increased rapidly. In India, 381 g/ha of chemical and synthetic pesticides are consumed annually and the rate of consumption rising from 2 to 5% yearly. However, the pesticides consumption is relatively lower in India than the worldwide consumption of 500 g/ha (Vendan, 2016). Chemical and synthetic pesticides are used in excessive amounts to control pests in crop fields and it also deteriorates the soil fertility and ecosystem (Zhang et al., 2011; Zhang, 2018). But it is the most effective tool for integrated pest management (IPM) (Kumari et al., 2014). However, they also have adverse impacts on water quality, soil health, product quality, and developed problems such as insect resistance, genetic variation in plants, toxic residues, food, and feed. The used pesticides may damage the indigenous microorganisms, disturb the soil ecosystem, also reduce the soil enzymatic activities that act as a "biological index" of soil fertility, and may also affect human health via the food chain (Monkiedje and Spiteller, 2002; Antonious, 2003; Ingram et al., 2005; Wang et al., 2006; Littlefield-Wyer et al., 2008). Soil biota when interacting with pesticides, then metabolic activities of soil biota may be affected substantially. Therefore, alteration in the physiological behaviour and biochemical reactions like mineralisation of organic matter, nitrogen fixation, nitrification, denitrification, and ammonification via activating or deactivating soil enzymes or soil microorganisms may happen.

Microorganisms are the key indicators of soil health and biological processes in the soil environment. But, heavy pesticide use significantly damages nitrogen fixation and phosphorus solubilising processes that maintain natural soil fertility and soil functioning (Singh and Walker, 2001; Kinney et al., 2005; Menon et al., 2005; Hussain et al., 2009). Chemical and synthetic pesticides are used expansively worldwide, but they are environmentally objectionable. Thus, reliance on chemical or synthetic pesticides and their extensive use has caused negative impacts on the environment and human health (Zhang et al., 2011). However, adverse effects of pesticides in the soil ecosystem have been observed from several parts of the country where pesticide use is widespread. Recognising the negative impact of the agrochemicals like pesticide resistance and residues in the produce, pest resurgence and outbreak of secondary pests, causes serious impacts on air, water, and soil (Al-Zaidi et al., 2011; Zhang and Liu, 2022). It has become necessary to develop substitutes for these synthetic agro-inputs due to the evolution of pesticide resistance in some pest species and concerns about the safety of chemical residues. The need of the day is to produce maximum from the diminishing natural resources and protect the produce from post-harvest losses without adversely affecting the environment.

One solution is using biopesticides (pest control agents based on living organisms) as a substitute in food production, but the rate of commercialisation is low (Fig. 1). Biopesticides are usually microbial biological pest control agents that are used in crop fields like chemical pesticides (Sanjaya et al., 2013; Zhang, 2018). The most beneficial advantages of biopesticides are that they are eco-friendly and have biodegradable by-products. They can be more affordable than chemical pesticides when locally produced. They can be more effective than chemical pesticides in the longterm. The utilization of biofertilisers and biopesticides can play a significant role in dealing with these challenges in a sustainable manner.

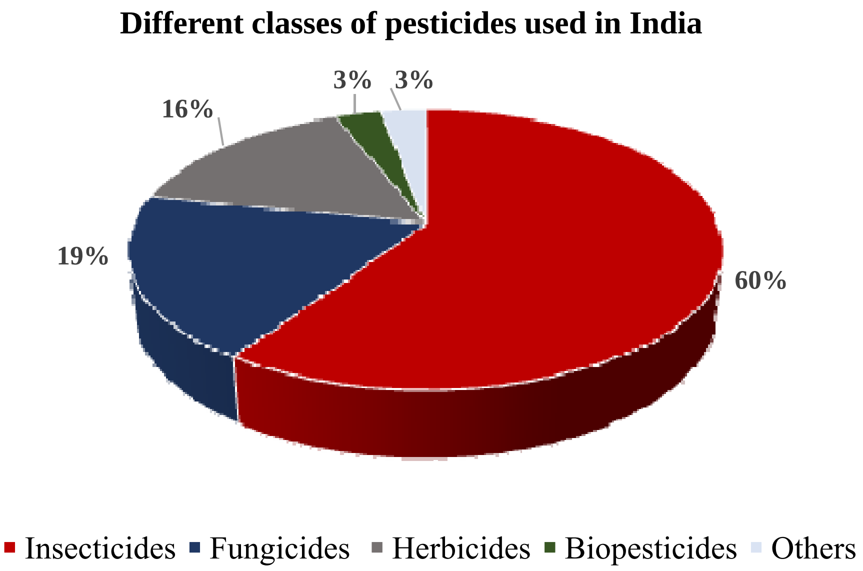

Fig. 1 The ratio of different classes of pesticides used in India (%).

Biopesticides and biofertilisers, the eco-friendly naturally occurring formulations made from the substances that control pests by non-toxic mechanisms and have been used in different forms since human civilisation. Biopesticides have more potential benefits to agriculture as well as public health programs. Biopesticides are naturally occurring products made from living organisms and have a minor threat to the environment and human health. It constitutes mainly naturally occurring substances termed biochemical pesticides. Secondly, it is also supported by microorganisms that control pests termed as microbial pesticides and, lastly, pesticide substances produced by genetic material termed as plant-incorporated protectants (Sarwar et al., 2013, Sarwar, 2015). Biopesticides consist of various microbial pesticides, biochemicals generated from microbes, and other natural sources. These are usually made by growing and concentrating naturally existing organisms and their metabolites, such as bacteria and other microorganisms, fungus, nematodes, etc. These are frequently considered vital components of IPM programs and have gained a lot of practical attention as alternatives to chemical and synthetic pesticides (Glare et al., 2012).

About 200 plants are known for insecticidal activities (Singh et al., 2001). But their accessibility is decreasing as a result of new regulations and pest populations evolution. Biopesticides are mass-produced agents manufactured from a living microorganism or a natural product and sold to control plant pests (Organisation for Economic Co-operation and Development (OECD), 2009). Biopesticides could be derived from animals (e.g., nematodes), plants such as *Chrysanthemum, Azadirachta* (Neem), and microorganisms (e.g., *Bacillus thuringiensis*, *Trichoderma, Pseudomonas*), and include living organisms (natural enemies), their product (phytochemicals, microbial products) which can be used for the management of pest injurious (Mazid et al., 2011).

Thus, biopesticides can be utilised for the management of pests. *Bacillus thuringiensis*, also known as Bt, is one of the most frequently used microbial biopesticides. The potential benefits of the utilisation of biopesticides in agriculture and public health programs are considerable. The present paper provides a baseline overview of biopesticides and their classifications, current status, and future prospects.

2 Materials and Methods

To gather more and more information about the biopesticides have extensively searched on available databases *viz* Web of Science, Google Scholar, Science Direct etc. using keywords biopesticides, biopesticides available in India, current scenario of biopesticides usage etc. We gathered all these articles from year 1985 to 2021 by using all above mentioned databases. From all above mentioned databases we got approx. 320 articles and approx. 80 from other additional sources including books, grey matter (unpublished thesis), reports, etc. After removing duplicate, insignificant and inappropriate studies finally, approx. 116 more relevant studies were included for preparation of the paper as shown in Fig. 2. The study conducted using secondary data. The major objective of the study is about awareness of biopesticides usage instead of chemical and synthetic pesticides in the current developmental era for the welfare of humankind. Biopesticides are an eco-friendly method to control pest and also a better substitute to the chemical pesticides.

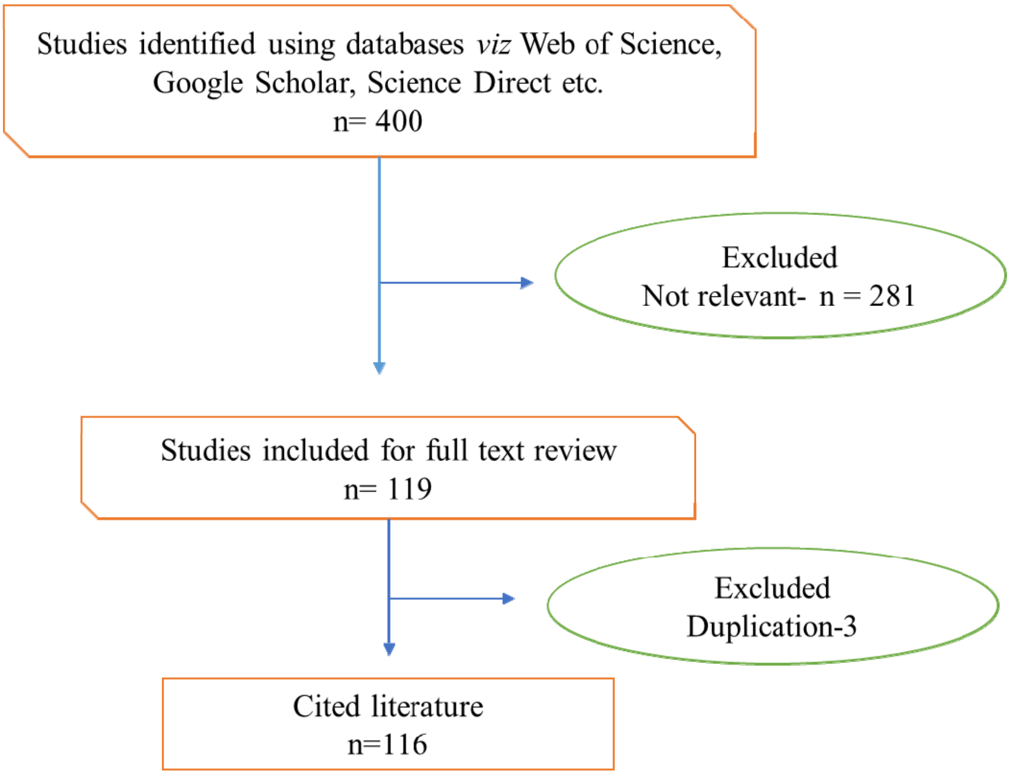

Fig. 2 Collection of relevant literature for the preparation of the present paper.

3 What Are Biopesticides?

Biopesticides are pesticides derived from microorganisms or natural products orbio-based formulations that control pests through different mechanisms of action (Tijjani et al., 2016). Plants, insects, and microorganisms are the primary source of biopesticides which are cheaper, readily available, demonstrate various modes of action, and are degradable. They are products or by-products derived from microorganisms (*Bacillus thuringiensis*, *Verticillium lecanii*, *Neodiprion sertifer*), insects (*Trichogramma* spp.), animals (nematode, *Heterorhabditis* spp.), and plant parts or extracts (*Chrysanthemum cinerariafolium, Azadirachta indica*)

(Pavela, 2014; Rodgers, 1993). They are categorised into (a) microbial biopesticides containing microorganisms controlling diseases and insects, (b) botanical biopesticides (plant-derived), and (c) plant-incorporated protectants (Fig. 3). In past few decades, biopesticides are the best substitute against chemical and synthetic pesticides in managing pests. They are currently used in the post and pre-harvest control of diseases and crop pests (EPA, 2011; Yadav, 2017; Kour et al., 2020). Biopesticides are target-specific and are nontoxic to the environment and humans. The mode of action of biopesticides is specific and operates by targeting pests. Nowadays, biopesticides have been played a vital role in the agro-market and are widely utilised in organic farming (Seiber et al., 2014; Nawaz et al., 2016; Lengai and Muthomi, 2018).

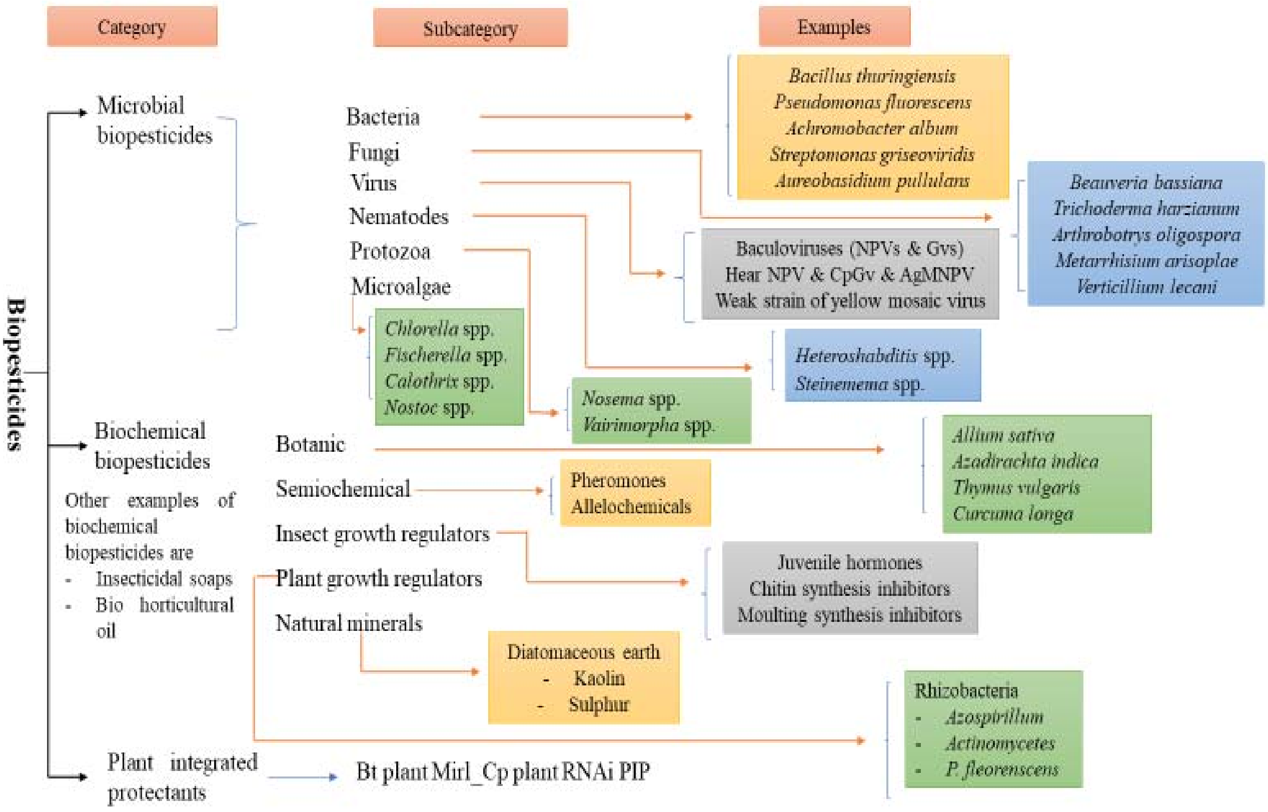

Fig. 3 The three different categories of biopesticides and some selected examples of each category.

More than 6000 species of plants have been showing insecticidal properties. Several products are derived from the plant in pest management, such as neem, tobacco, pyrethrum, and custard apple (Koul, 2012). Due to their volatile nature, these plant-derived pesticides are eco-friendly with minimal environmental risk compared to chemical pesticides. Azadirachtin derived from neem plant is sold under numerous trade names; we use it against several food crops to control the population of thrips, scale, and whitefly (Sarwar et al., 2013). Some important botanical biopesticides are given in Table 1. Many problems encountered during the commercialisation of plant derived pesticides include product standardisation and quality control. The improper and excessive application of plant-derived pesticides also leads to resistance in insect pests, as showed by synthetic pesticides. Phytotoxicity is also noticed in plant-derived pesticides, e.g., neem oil is phytotoxic to brinjal, tomato, and ornamental plants (Stevenson et al., 2012). Some plant products registered as biopesticides and their products with target organisms are listed in Table 2.

Table 1 List of important plant-derived pesticides with their target organisms.

Source	Target Species	References
Azadirachta indica	*Aspergillus species, Aphis craccivora, Amrasca devastans, Alternaria alternate, Bacillus subtilis, Aphis gossypii, Bemisia tabaci, Sitobionavenae, Helminthosporium* species, *Lipaphis erysimi, Meloidogyne javanica, Meloidogyne incognita, Myzus persicae, Sciothrips cardamom, Monilinia fructicola, Rhizopus* species, *Vibrio cholera, Pythium aphanidermatum,* and *Trichothecium roseum*	Baidoo et al. (2012), Vinodhini and Malaikozhundan (2011), Aziz et al. (2013), Biswas (2013), Stanley et al. (2014), Raut et al. (2014), Castillo-Sa´nchez et al. (2015)
Allium sativum	*Alternaria raphanin, Aspergillus niger, Bacillus subtilis, Brevicoryne brassicae, Bipolaris sorokiniana, Candida albicans, Curvularia lunata, Colletotrichum* species, *Callosobruchus maculatus, Fusarium graminearum, Fusarium flocciferum, Drechslera tritici-repetis, Plutella xylostella, Salmonella senflenberg, Rhizoctonia solani, Staphylococcus aureus, Staphylococcus epidermidis, Sitotroga cerealella, Spodoptera littorals, Trichophyton rubrum,* and *Tenebrio molitor*	Yang et al. (2012), Perello et al. (2013), Suleiman and Abdallah (2014), Tiroesele et al. (2015), Ghotaslou et al. (2016), Strika et al. (2017), Baidoo and Mochiah (2016), Plata-Rueda et al. (2017)
Curcuma longa	*Alternaria solani, Bactrocera zonata, Bacillus subtilis, Listeria monocytogenes, Escherichia coli, Tribolium castaneum, Trichoplusia ni, Streptococcus pyogene, Streptococcus mutants,* and *Ralstonia solanacearum*	Ali et al. (2014), Siddiqi et al. (2011), Mohammed and Habil (2015), Murthy et al. (2015), Rawat and Rawat (2015), de Souza Tavares et al. (2016), Altunatmaz et al. (2016), Muthomi et al. (2017)
Cinnamomum zeylanicum	*Bursaphelenchus xylophilus, Aspergillus oryzae, Botrytis cinereal, Bacillus subtilis, Escherichia coli, Fusarium solani, Staphylococcus aureus, Penicillium expansum,* and *Meloidogyne* species	Shirurkar and Wahegaonkar (2012), Bastas (2015), Nikkhah et al. (2017), Zhang et al. (2016)
Euphorbia spp.	*Aspergillus flavus, Enterobacter aerogenes, Escherichia coli, Salmonella typhi,* and *Pseudomonas aeruginosa*	Gayathri and Ramesh (2013), Mohammadi et al. (2016), Voukeng et al. (2017)
Jatropha spp.	*Aspergillusn flavus, Alternaria alternate, Meloidogyne incognita, Aphis fabae, Bactrocera cucurbitae, Penicillium glabrum, Oryzaephilus surimanensis, Rhyzorpertha dominica, Tribolium castaneum,* and *Sitophilus zeamais*	Srivastava et al. (2012), Asif et al. (2014), Rampadarath et al. (2016), Neeraj et al. (2017)
Tagetes spp.	*Brevicorynebrassicae, Fusarium oxysporum, Mamestrabrassicae, Klebsiella pneumoniae, Plutellaxylostella, and Meloidogyne incognita*	Jankowska et al. (2009), Bissa and Bohra (2011), Granja et al. (2014)
Thymus vulgaris	*Aspergillus niger, Meloidogyne incognita, Diaphorina citri, Megalurothrips sjostedti, Escherichia coli, Pratylenchus brachyurus, Helicotylenchus dihystera, Saccharomyces* species, *Penicillium* species, *Tilletia tritici*, *Salmonella typhimurium,* and *Xanthomonas vesicatoria*	Abtew et al. (2015), Witkowska et al. (2016), Karaca et al. (2017), Semeniuc et al. (2017)
Zingiber officinale	*Aspergillus parasiticus, Aspergillus flavus, Drosicha mangiferae, Dermestes maculatus, Fusarium oxysporum, Escherichia coli, Rhizoctonia solani, Pythium aphanidermatum, Necrobial rufipe, Trichoplusia binotalis, Salmonella typhi,* and *Tribolium castaneum*	Al-Rahmah et al. (2013), Abid and Butt (2015), Rizvi et al. (2016), Ayeloja and George (2016)

Source- Modified from Thakur et al. (2020).

Table 2 Some of the plant's products are registered as biopesticides and their products with target organisms.

Botanical Pesticides	Target Organism
Neem	Sucking and chewing insect (Aphids, Thrips, lepidopteran and coleopteran larvae such as apple codling moth, cotton bollworm, green leafhopper, etc.), nematodes and fungi (*Rhizoctonia solani*, *Fusarium oxysporum*, *Botrytis cinerea*, etc.)
Linalool and Limonene	Aphids, fleas, fire ants, mites, flies, house crickets, and paper wasps
Nicotine	Used as a fumigant against the soft-bodied insect pests
Pyrethrum	Mosquitoes, caterpillars, sawfly larvae, aphids, leafhoppers, house flies, *Culicoides variipennis*, ants, flour beetle, fleas, flies, cockroaches, and ticks
Rotenone	Aphids, beetles (bean leaf beetle, Colorado potato beetle, asparagus beetle, flea beetle, cucumber beetle, fleas, strawberry leaf beetles), and lice
Ryania	Caterpillars (European corn borer, corn earworm, and thrips)
Sabadilla	Harlequin bugs, squash bugs, leafhoppers, thrips, stink bugs, and caterpillars

Source- Modified from Mazid et al. (2011), and Sachdeva and Singh (2016).

Table 3 Bioinsecticides available in India.

Biocontrol Agents	Product Name	Against Pests
Bacillus thuringiensis subsp. *Israelensis*	Tacibio/Technar	Leipdopterous pests
B. thuringiensis subsp. *Kurstaki*	Bio-Bart/ Biolep/Halt/Taciobio-Btk	Lepidopterous pests
Baeuveria bassiana	Myco-Jaal/Biosoft/ATEC/Baeuveria/Larvo-Guard/Biorin/Biolarvex/Phalada 101B/Biogrubex/Biowonder/Veera/Bioguard/Bio-power	Coffee-berry borer, diamondback moth, thrips, grasshoppers, whiteflies, aphids, coding moth
Helicoverpa armigera NPV	Helicide/Helocide/Biovirus-H/Heligard/Virin-H	Cotton bollworm
Metarhizium anisopliae	ABTEC/Verticillium/Meta-Guard/Biomet/ Biomagic/Meta/Biomet/Sun Agro Meta/Bio-Magic	Coleoptera and lepidoptera, termites, mosquitoes, leafhoppers, beetles, grubs
Pseudomonas fumosoroseus	Nemato-Guard	Whitefly
Pseudomonas lilacinus	Yorker/ABTEC/Paceilomyces/Paecil/Pacihit/ROM biomite/Bio-Nematon	Whitefly
Verticillium lecanii	Verisoft/Verticillium/Vert-Guard/Bioline/Biosappex/Versitile/Ecocil/Phalada 107 V/Biovert Rich/ROM Verlac/ROM Gurbkill/Sun AgroVerti/Bio-Catch	Whitefly, green coffee bug, homopteran pests
Spodoptera litura NPV	Spodocide/Spodoterin/Spodi-cide/Biovirus-S	*Spodoptera litura*

Source- Modified from Mishra et al. (2015).

Biopesticides play a vital role in crop protection. They are compatible with other chemical pesticides and are also utilized in integrated crop management (ICM) practices throughout the world. Due to advancements in research and development, biopesticides have raised sustainability and reduced the pollution caused by chemical pesticides. Production of biopesticides is challenging due to the dissimilarity of the active and integrated ingredients. Moreover, when utilised as a component of IPM programs, biopesticides achieve an equivalent level of crop yield by reducing the load of chemical pesticides (Aneja et al., 2016; Satapathy, 2018; Zhang and Liu, 2022). Commonly used biopesticides are living organisms, which have pathogenic potential against pests. These consist of bioinsecticides (*Bacillus thuringiensis*) (Table 3), biofungicides (*Trichoderma*) (Table 4), and bioherbicides (*Phytopthora*) (Table 5). Approximately 24 bioherbicides have been registered in the world so far. Out of these, ten are registered in the USA, eight in Canada, three in South Africa, and one each in Japan, Netherlands, India, and China (Dagno et al., 2012; Aneja et al., 2014; Harding and Raizada, 2015). Auld et al. (2003) reveal in research findings that bioherbicide products have low cost, long shelf-life, ease of application, and efficacy.

Biopesticides are easily available in nature, easily biodegradable, show different modes of actions, are less expensive and possess less toxicity to live organisms. Therefore, it was realised that biological control is the only means of a safe, cost-effective, and eco-friendly method to control the widespread resistance of chemical insecticides towards pests. Later, biopesticides became a part of IPM that was previously wholly based on chemical pesticides (Mishra et al., 2020). Globally, research on the application and stability of diverse biopesticides can help to assist sustainable agriculture (Kumar et al., 2019; Yadav and Yadav, 2019).

Table 4 Some biofungicides developed and commercialised around the world.

Biocontrol Agents	Product Name	Target Pathogens	Crops
Agrobacterium radiobacter K84	GALLTROL	*Agrobacterium tumefaciens*	Ornamental nursery stock, soil treatment
Bacillus subtillis QST 713	CEASE	*Rhizoctonia solani, Pythium, Phythophora, Fusarium*	Most greenhouse ornamentals and vegetable transplants
Bacillus subtillis GB03	COMPANION (LIQUID)	Leaf spots, Powdery mildew, Botrytis, bacterial diseases, *Rhizoctonia solani, Pythium, Phytophthora*	Most greenhouse ornamentals and vegetable transplants
Bacillus subtilis	EPIC (Dry powder).	*Fusarium* spp., *Rhizoctonia solani, Alternaria* spp., *Aspergillus* spp.	Cotton and legumes
Bacillus subtilis	KODIAK, KODIAK HB, KODIAK A.T (Dry powder)	*Rhizoctonia solani*, *Alternaria* spp., *Aspergillus* spp., *Fusarium* spp.	Cotton and legumes
Coniothryium minitans	CONTANS WG	*Sclerotinia sclerotiorum, S. minor*	Most greenhouse ornamentals, vegetable transplants, herbs, Soil treatment
Gliocladium virens GL-21	SOIL GARD	*Rhizoctonia solani, Phytium*	Most greenhouse ornamentals, vegetable transplants
Gliocladium catenulatum JII-446	PRESTOP WP	*Botrytis, Rhizoctonia solani, Pythium* spp., *Phytophthora, Fusarium, Verticillium* spp.	Most greenhouse ornamentals, vegetable transplants

Fusarium oxysporum (nonpathogenic)	FUSACLEAN (spores)	*Fusarium oxysporum*	Asparagus, basil, carnation, tomato
Myrothecium verrucaria	DITERA (Wettable powder)	Root knot, citrus cyst, stubby root, lesions and burrowing nematodes	Fruit vegetables and ornamental crops, turf
Pseudomonas cepacian	INTERCEPT	*Fusarium* spp., *Rhizoactonia solani*, *Pythium*	Maise, vegetables, cotton
Psudomonas fluorescens	PHAGUS (Bacterial Suspension)	*Pseudomonas tolassii*	*Agaricus* spp., *Pleurotus* spp.
Reynoutria sachalinensis	REGALIA	*Botrytis,* Leaf Spots, Powdery mildew, bacterial diseases, *Fusarium, Rhizoctonia, Pythium, Phytophthora, Verticillium*	Herbs and spices, soil treatment, plant health promoter
Streptomyces griseovirdis	MYCOSTOP (Dry powder)	*Botrytis, Rhizoctonia, Pythium, Phythophora, Alternaria*	Most greenhouse ornamentals, vegetable transplants
Streptomyces lydicus	ACTINOVATE	Powdery mildew, Downy mildew, *Botrytis, Rhizoctonia, Pythium, Phytophthora*	Most greenhouse ornamentals, vegetable transplants
Tricoderma harzianum	PLANT SHIELD, ROOT SHIELD, T-22 PLANTER BOX	*Cylindrocladium, Fusarium, Rhizoctonia, Pythium, Thielaviopis*	Most greenhouse ornamentals, vegetable transplants

Source- Modified from Burges (1998), and Aneja et al. (2016).

Table 5 Some commercial bioherbicides are available and used globally.

Biocontrol Agents	Product Name	Formulation Type	Target Weed	Year of Registration and Country
Acremonium diospyri	ACREMONIUM DIOSPYRI	Conidial suspension	Persimmon (*Diospyros virginiana*) trees in rangelands	1960 Canada
Colletotrichum gloeosporioides f. sp. *Cuscutae*	LUBAO	Conidial suspension	Dodder (*Cuscata chinesis and C. australis*) in soyabeans	1963 China
Phytophthora palmivora (P. citrophthora)	DEVINE^R	Liquid spore's suspension	Milkweed vine (*Morrenia odorata*)	1981 USA
Colletotrichum gloeosporioides f. sp. *Aeschynomene*	COLLEGO^{TM} (LOCKDOWN^{TM})	Wettable powder	Northern joint-vetch (*Aeschynomene virginica*)	1982 USA
Alternaria cassia	CASST^{TM}	Solid	Sickle-pod and coffee senna (*Cassia* spp.)	1983 USA
Cercospora rodmanii	ABG-5003	Wettable powder	Water hyacinth (*Eichhornia*	1984 USA

			crassipes)	
Puccinia canaliculate	DR. BIOSEDGE	Emulsified suspension	Yellow nutsedge (*Cyperus esculentus*)	1987 USA
Colletotrichum coccodes	VELGO[R]	Wettable powder	Velvet leaf (*Abutilon theophrastus*)	1987 Canada
Colletotrichum gloeosporioides f. sp. *Malvae*	BIOMAL[R]	Wettable powder in silica gel	Round-leaved mallow (*Malva pussila*)	1992 Canada
Cylindrobasidium	STUMPOUT[TM]	Liquid (oil) suspension	Turf grass (*Poa annua*) in golf courses, *Acacia* spp.	1997 South Africa
Chondrostereum purpureum	BIOCHON[TM]	Mycelial suspension in water	Woody plannts Blackberry weed (*Prunus serotina*)	1997 Netherlands
Xanthomonas campestris pv *poae*	CAMPERICO[TM]		Turf grass (*Poa annua*)	1997 Japan
Colletotrichum acutatum	HAKATAK	Conidial suspension Granular Dry Conidia	*Hakea gummosis* & *H. sericea* in native vegetation	1999 South Africa
Puccinia thlaspeos	WOAD WARROIR	Powder	*Isastis tinctoria* (dyer's wood or glastrum) in farms and rangeland	2002 USA
Chondrostereum purpureum	MYCOTECH[TM] PASTE	Paste	Deciduous tree species	2002/2005 Canada
Chondrostereum purpureum	CHONTROL[TM] PASTE	Spray emulsion & paste	Alder, aspen and other hardwood	2004/2005 Canada
Alternaria destruens	SMOLDER[R]	Conidial suspension	Dodder species	2005 USA
Sclerotinia minor	SARRITOR	Granular	Dandelions in lawns/turf	2007 Canada
Fusarium oxysporum f. sp. *Stigae*	STRIGA	Solid, Dried Chlamydospores+ Arabic gum	*Striga hermonthica* & *S. asiatica*	2008 Africa
Tobacco mild green mosaic virus	SOLVINIX[TM]	Wettable powder/ Foliar spray suspension	Soda apple (*Solanum viarum*)	2009 Florida
Lactobacillus spp. *Lactococcus* spp.	ORGANO-SOL	Liquid	Broadleaved weeds	2010 Canada
Phoma macrostoma	Formulation Product name not Specified	Granules composed of mycelial fragments and flour	Broadleaved weeds	2011 Canada/USA
Streptomyces spp.	MBI-005 EP		Broadleaved weeds	2012 USA
Gibbagotrianthemae	GIBBATRIANTH	Liquid Conidial Suspension+ Surfactant	*Trianthema portulacastrum* (Horse purslane)	2014 India

Source: Modified from Aneja, 2014.

4 Current Global Status of Biopesticides

The biopesticides' total production is 3000 tonnes per year, and their use is enhancing steadily by 10% every year (Gupta and Dixit, 2010; Kumar and Singh, 2015). Marrone (2007) states that about 1400 biopesticide products are prepared and sold worldwide. Over 200 biopesticides are sold in the US market as compared to only 60 similar products available in the European Union (EU) (EPA, 2012). About 45% of biopesticides were used and sold in the USA, Canada, and Mexico (NAFTA Countries). In comparison, Asia lacks biopesticides and uses only 5% of biopesticides sold globally (Bailey et al., 2010; Hubbard et al., 2014).

The biopesticides market holds apretty small share in the crop protection market of the world. The worldwide biopesticides market was approximately 3.5% ($1.6 billion) of the total pesticide market of the world in 2009 (BCC Research, 2010), which grown to 5% ($3 billion) (Olson et al., 2013). However, its rate of growth shows an increasing trend in the past two decades. Approximately up to 2023, the annual growth rate of biopesticides will rise to 8.64% and account for more than 7% ($4.5 billion) of the worldwide crop protection market (Olson, 2015). Most countries have improved their policies to reduce the utilization of chemical pesticides and promote biopesticides; however, biopesticides are still primarily regulated by the system initially designed for chemical pesticides (Kumar and Singh, 2014). Due to very long and complicated processes of registration in the European Union (Poinar Jr and Leutenegger, 1968), a minimal number of biopesticides have been registered as compared to Brazil, United States, China, and India (Damalas and Koutroubas, 2018). In Nigeria, the utilization of biopesticides is low due to substandard foundations, high costs, and governmental policies (Ivase et al., 2017). In China, 327 biopesticides were registered. Two hundred seventy bacterial biopesticides were produced from 11 species of microbes, among which 181 biopesticides were produced from *B. thuringiensis* (ICAMA, 2008). In 2002, total biopesticides, mainly *B. thuringiensis*, weresoldat1.5 million dollars in Kenya alone (Wabule et al., 2004; Abtew et al., 2015).

4.1 Current Indian status of biopesticides

The biocontrol concept of plant diseases has been started in India for an extended time (Schmutterer, 1985). The neem tree (*Azadirachta indica* A. Juss) and its derivatives, such as leaf extract, oil, and seed cake, have been used as fertilizers to minimise the risk of post-harvest loss in stored storage cereals (Isman, 1997; Brahmachari, 2004). During the 1960s, with a target of judicious use of pesticides in agriculture, the concept of IPM had also arisen (Smith and van den Bosch, 1967). However, in India, a major technological breakthrough in biocontrol ocuured when conventional insecticides failed to control *Helicoverpa armigera*, *Spodoptera litura*, and other cotton pests (Kranthi et al., 2002).

Also, the awareness about the utilisation of biopesticides among the farmers is enhancing and hence it becomes a very popular alternative to the chemical and synthetic pesticides (Pelaez and Mizukawa, 2017). Biopesticides are registered and regulated under the Insecticides Act, 1968 (Satapathy, 2018). In India, 2.5% is the estimated annual rate of growth of biopesticides. Due to some issues at the policy and industrial level, the production of biopesticides is relatively lower in India. In India, the consumption of biopesticides produced from plant-derived is less than 1% and is only 12% globally. For sustainable farming, National Farmer Policy 2007 has promoted the utilization of biopesticides (Dar et al., 2004). In India, only twelve types of biopesticides have been registered under the Insecticide Act, 1968 India (Table. 6), which shows different biopesticides formulated in various industries (Fig. 4).The trend of biopesticides consumption in India has shown a drastic increase in uses over time which stood at 8847 and 8645 metric tonnes in 2019-20 & 2020-2021, respectively (Fig. 5).

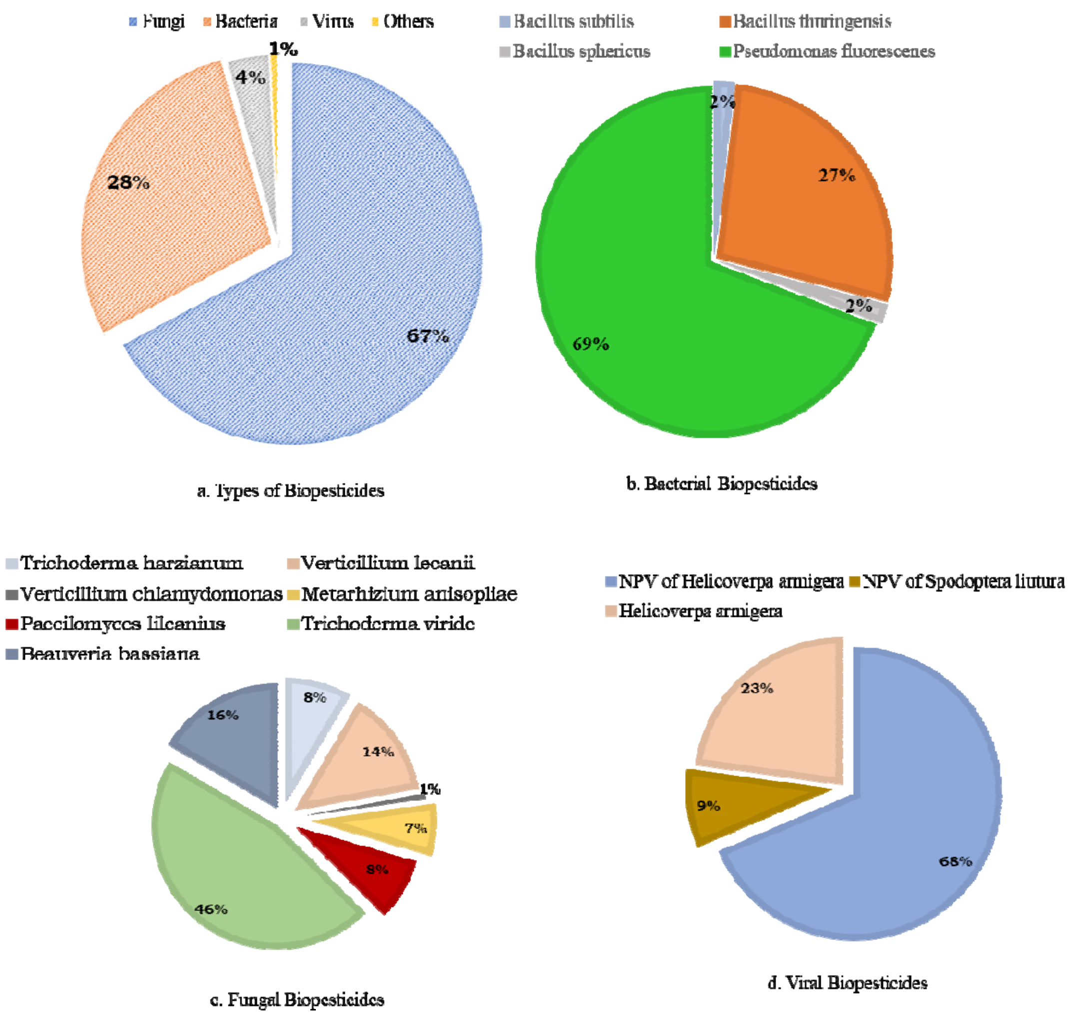

Fig. 4 Industry-wise distribution of microbial biopesticides (Source: Data obtained from DPPQS, Ministry of Agriculture & Farmers Welfare, Government of India).

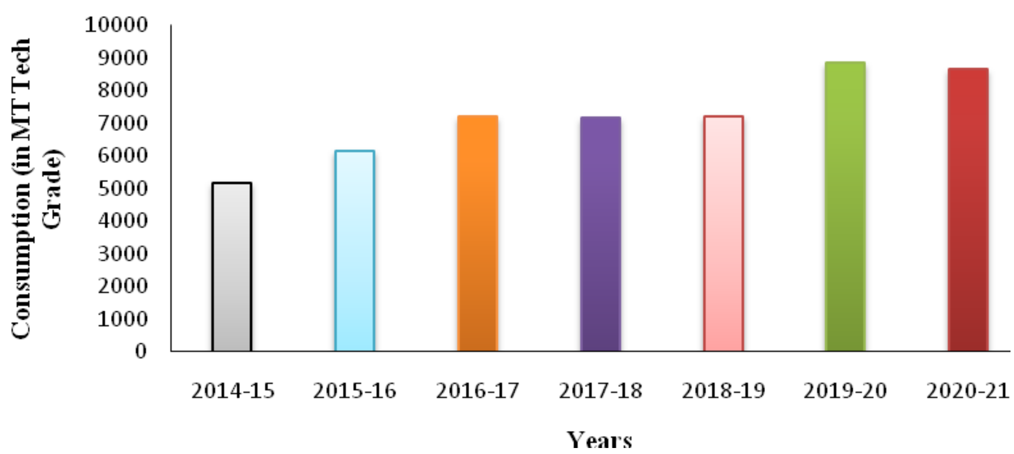

Fig. 5 Consumption of biopesticides in India during the last seven years (Source: Data obtained from DPPQS, Ministry of Agriculture & Farmers Welfare, Government of India).

Table 6 List of biopesticides registered in India under Insecticides Act, 1968.

Sr. No.	Name of Biopesticides
1	*Bacillus thuringiensis* var. *israelensis*
2	*Bacillus thuringiensis* var. *kurstaki*
3	*Bacillus thuringiensis* var. *galleriae*
4	*Bacillus sphaericus*
5	*Trichoderma viride*
6	*Trichoderma harzianum*
7	*Pseudomonas fluorescens*
8	*NPV of Helicoverpa armigera*
9	*Beauveria bassiana*
10	NPV of *Spodoptera litura*
11	Neem based pesticides
12	*Cymbopogon*

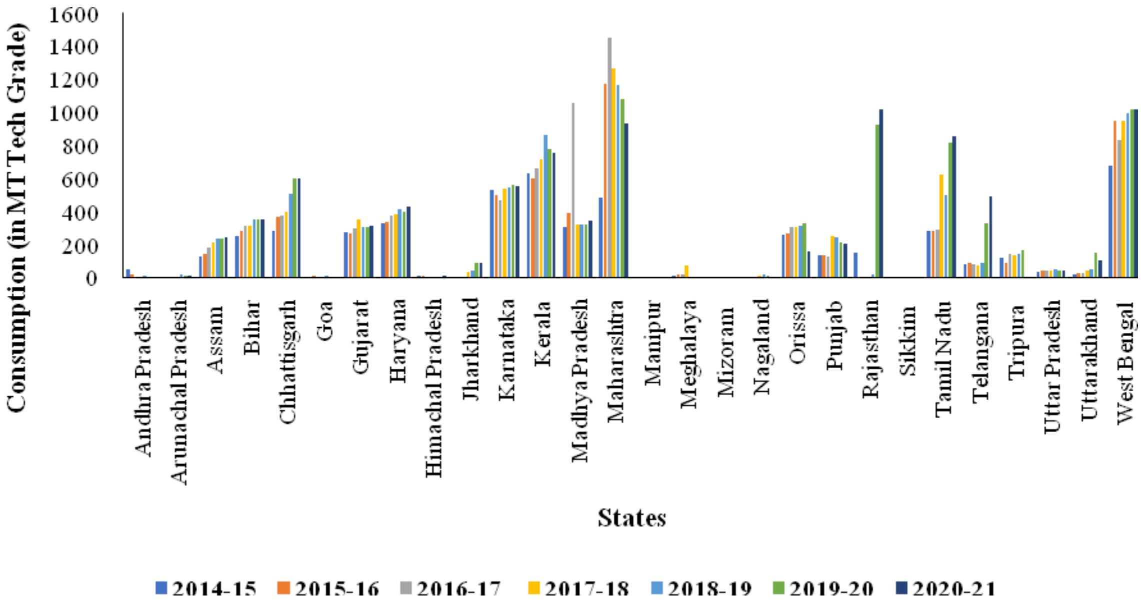

Fig. 6 Consumption of biopesticides formulation in various states of India during 2014-15 to 2020-21 (Source: Data obtained from DPPQS, Ministry of Agriculture & Farmers Welfare, Government of India).

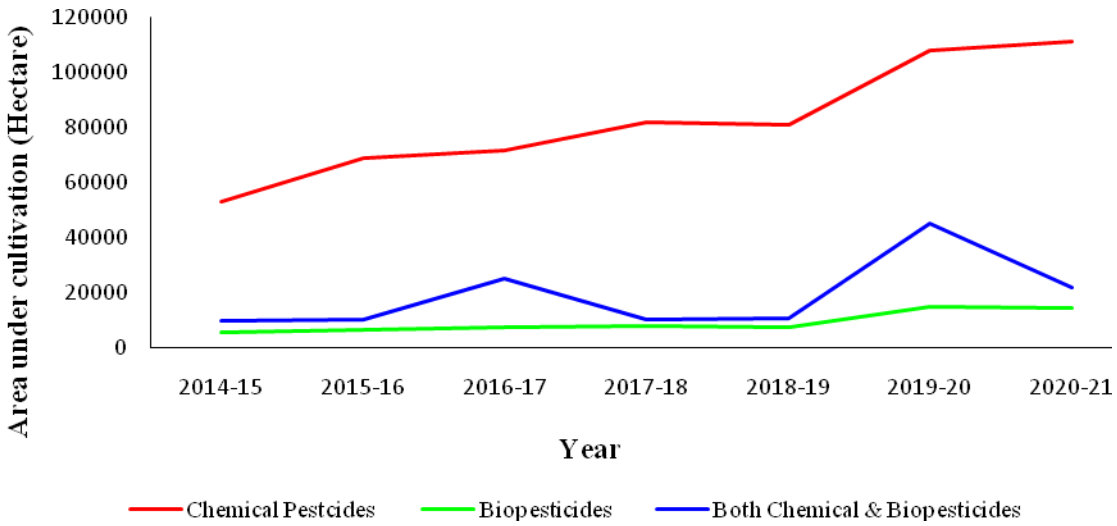

Fig. 7 Area under cultivation and use of chemicals & biopesticides during 2014-15 to 2020-21 (Source: Data obtained from DPPQS, Ministry of Agriculture & Farmers Welfare, Government of India).

In recent years, there has been a tremendous increase in the use of biopesticides, and the area of cultivation of biopesticides has been rapidly increasing. In India, West Bengal, Rajasthan, and Maharashtra used the maximum amount of biopesticides in 2020-21. Fig. 6 and Fig. 7 represents the consumption of biopesticides formulation in various states of India during 2014-15 to 2020-21 and the area under cultivation and underuse of chemical & biopesticides during 2014-15 to 2020-21 respectively. The rapid growth in the biopesticide market is based on the advantages such as inherently less harmful, reduced environmental load, affecting only one specific pest or a few pests in some cases, degradable therefore decrease exposure to the biota, thus avoiding the pollution problems, also effective in small quantities, and nontoxic to humans.

5 Future Prospects

Improve product quality and sales through technical inputs and training to producers. There is a need for more communication between users, researchers, and industry in the early stages of their development to gear up biopesticide research.

- The government should continue imposing strict regulatory measures on conventional chemical pesticides. It will create a big opportunity for biopesticides marketing to help fill the gap and the availability of biopesticides at affordable cost.
- To promote these eco-safe approaches, encourage and empower developing countries to develop their biopesticide manufacture and use capacities.
- Incorporation of biopesticides in the mainstream of agriculture requires a better understanding of action mechanisms to enhance their activity spectra against pests, improving their field performance, advancement in the delivery system of biopesticides, longer shelf life, low cost of production, ease of availability, awareness among farmers and simple registration and regulation policy (Fig. 8).

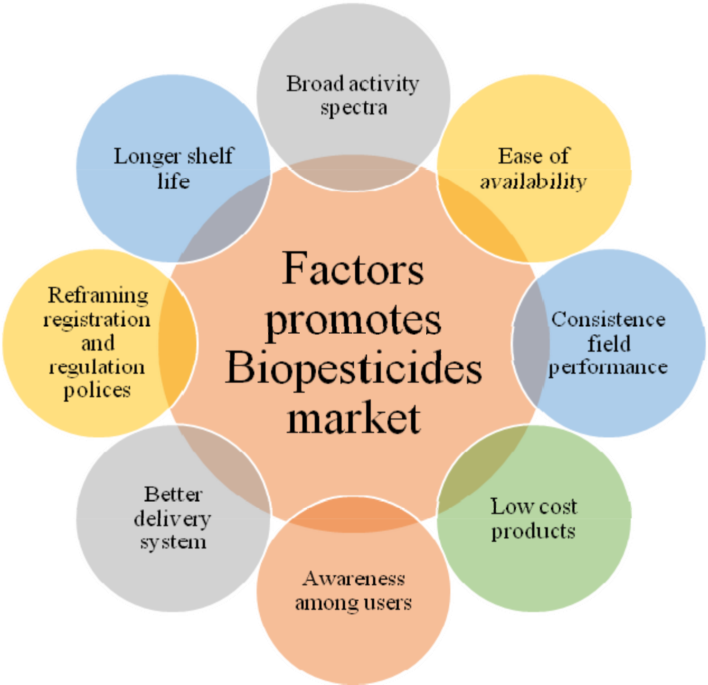

Fig. 8 Factors that promotes the biopesticides market.

- The most significant advances in biopesticides will come by exploiting knowledge of pests' genomes and their natural enemies. Researchers are using molecular-based technologies to reconstruct the evolution of natural microbial enemies and separate the molecular basis for their pathogenicity. An ecological study on the dynamics of disease in the insect population is necessary.
- Farmers should be adequately trained to use biopesticides for harvesting maximum benefits. The primary constraints include: creating awareness among farmers on biopesticides storage and use; farmers should be adequately trained to use these eco-friendly alternatives to pest control in their agricultural fields efficiently.

Moreover, efforts should be made to minimise the loss of infectivity of pathogens due to photoinactivation. Make aware of the uses and benefits of biopesticides among the farming community is the priority.

6 Challenges for Biopesticides

Biopesticides are considered safe because they are target-oriented, reduce environmental pollution risk, and eliminate resistance. Biopesticides are gaining popularity due to the desire for safe and residue-free food. Despite all these beneficial attributes, in India biopesticides market is small. Farmers are unwilling to use biopesticides in place of chemical pesticides due to their high cost, inconsistent performance on fields, short shelf life, and delayed results. The biopesticides market is also affected due to the lack of large-scale production facilities. In India, the registration process is time-consuming and expensive and it also slows the development of biopesticides. Due to the high cost of raw materials and extraction process, commercial production of botanical pesticides is more expensive than chemical pesticides. However, the lack of awareness about biopesticide's benefits, knowledge about biopesticides products, confidence in farmers, and unreliable supply and inconsistent performance are major challenges in the development of biopesticides. Ecological studies are necessary on the dynamics of diseases in insect populations because environmental factors play a vital role in the outbreaks of the disease to control the pests.

7 Policy Recommendations

The following policy measures need to be taken urgently to reduce the excessive utilisation of chemical pesticides and promote the biopesticide industry and R & D in the same field.

- Focus on sustainable agriculture by promoting: a) disease and pest resistant, and mainly traditional, varieties; b) judicious inter-cropping, and c) reduced crop intensity.
- Improvement in the intensity of training for IPM. The focus should be on both the quality of training and the number of farmers trained. The training should be followed by regular contact with the trained farmers for providing continuous support.
- The state agricultural universities, which have a decisive influence over what governmental agencies promote pest control methods, should pay greater attention to biopesticides.
- Continued investment in expertise for the discovery, development, and implementation of biopesticides growth in industry research and development (R & D) is necessary to support the development and registration of more biopesticides. The underpinning fundamental through to early development research is often conducted in university and government research institutes. Together, public and private organisations are needed to educate growers, retailers, and the public on the use and merits of biopesticides.
- More research and trials on area-specific and crop-specific formulations are needed to maximize the use of biopesticides.
- Funding agencies should come forward for research and development of novel and innovative biopesticide formulation specific to pests.

The efforts of various government agencies to popularise integrated pest management (IPM) and the use of biopesticides have had little impact. In the absence of active promotion bythe agriculture department, the demand for these products has not developed and increased. For this reason, the majority of the private shops and dealers do not stock and sell biopesticides.

8 Conclusion

Pesticide resistance problems are faced by farmers most of the time. Due to these problems, microbial biopesticides are at the forefront of IPMs systems. Resistance in insect body against microbes is not developed quickly. Biopesticides are best for controlling the pests of agriculture than chemical pesticides. Productions and utilisation of biopesticides are increasing fast due to their eco-friendly with host-specific nature globally. Organic farming and agricultural produce free from pesticide residue would positively permit greater acceptance of biopesticides among the farmers. The National Farmer Policy of 2007 actively encouraged the development of biopesticides to manage pests in an environmentally acceptable manner. Biopesticide research is young and evolving and requires more attention and reliability. To develop biopesticides, deep analysis is needed, including screening potential control agents, formulation, delivery, and commercialisation. Biopesticides are attracting global attention as a safer, eco-friendly approach to managing pest populations such as weeds, plant pathogens, and insects while posing less risk to animals, humans, and the environment. As environmental safety is our primary concern, we need to develop awareness among the manufacturers, farmers, policymakers, government agencies, and ordinary men to promote biopesticides in pest management.

Therefore, biopesticides need to be explored more and people should be encouraged to use them instead of chemical pesticides. As it played a vital role in pest management strategies, their role will likely be more significant in agriculture and forestry in the future. Biopesticides have the potential to bring sustainability to global agriculture for food and feed security.

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