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Biopesticides an eco-friendly pest management approach in agriculture : status and prospects

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ABSTRACT

Agriculture is adversely affected by numerous pests like insects, weeds, plant pathogens and nematodes leading to reduced yield and poor quality of the produce. Biopesticides offer powerful tools to create a new generation of sustainable agriculture products and most likely alternatives some of the most problematic, pollution creating and carcinogenic chemical pesticides currently in use. These are the formulations based on the live organisms (e.g. fungi, bacteria, viruses) and their metabolites used to manage pests in agriculture. The present emphasis on the development and use of the biopesticides is based on the disadvantages associated with chemical pesticides. Globally, their use is increasing steadily at the rate of 10% per annum. Of the three classes of biopesticides, microbial pesticides are some of the earliest developed and widely used biopesticides. About 90% of the biopesticides are derived from just one entomopathogenic, endospore producing, Gram positive bacterium *Bacillus thuringiensis*, commonly called Bt. Though, India has a vast potential for biopesticides, however, these represent only 2.8% of the over all pesticide market. Biopesicides, although shows a great promise, have not come up to the desired level so as to displace the dominance of chemical pesticides. As environmental safety is a global concern, we need to create awareness among the farmers, government agencies, policy makers, manufacturers and the common man to switch-over to biopesticides for pest management requirements.

Key words: Pests, IPM, biochemical pesticides, microbial pesticides, neem, *Bacillus thuringiensis*, *Colletotrichum*, *Beauveria*, *Peniophora*

INTRODUCTION

Agriculture is adversely affected by numerous pests like insects, weeds, plant pathogens and nematodes from time immemorial reducing the estimated 45% crop losses amounting to around 290 billion per annum. The conventional chemical pesticides have although enhanced food production but have also adversely affected the environment and non target organisms. In addition, volatile pesticide residues also sometimes raised food safety concern among domestic consumers and pose trade empediments for export crops. Biopesticides - the formulations derived from natural materials (eg. bacteria, animals, plants, minerals) and living microbes (eg. fungi, bacteria, viruses) offer powerful ecofriendly tools to create a new generation of sustainable agricultural products. Globally, the use of biopesticides is increasing steadily by 10% per annum. The total world production of biopesticides is over 3000 tonnes per year and India have a vast potential for biopesticide production and consumption (Gupta and Dixit, 2010; Al-Zaidi *et al.*, 2011).

Biopesticides fall into three major classes, viz. microbial pesticides, plant pesticides (botanical pesticides) and biochemical pesticides. Interestingly, about 90% of the microbial pesticides are based on just one entomopathogenic endospore producing bacterium *Bacillus thuringiensis* (Kumar and Singh, 2015). Keeping in view the vast microbial biodiversity, there are ample opportunities for searching new/modifying potential biopesticides to save the environment from the lethal effects caused by agrochemicals on non target organisms, especially humans.

CATEGORISATION OF BIOPESTICIDES

Biopesticides (*bio+pest+cide*) are pesticidal formulations of living organisms (natural enemies) and substances (metabolite) derived from plants, animals, bacteria, and minerals which control pest by non toxic mechanism and eco-friendly manner. The environmental protection agency (EPA) of the United States separate biopesticides into three major classes based on the type of active ingredients used, namely plant-incorporated protectants called plant based pesticides (or botanical pesticides); biochemical pesticides; and microbial pesticides (USEPA, 2008). The International Biocontrol Manufacturer's Association (IBMA) and the International Organisation for Biological Control (IOBC) 2008 promote to use the term biocontrol agents (BCAs) instead of microbial pesticides.

Based on the natural resources from which the agents are isolated, biopesticides are classified as microbial pesticides, botanical pesticides, zooid pesticides and genetically modified plants (Leng *et al.*, 2011). As per the EPA of the United States, the biopesticides have been categorised as microbial pesticides (fungi, bacteria, viruses as active ingredients), biochemical pesticides or herbal pesticides or plant pesticides (naturally occurring substances of plants that control pests by nontoxic mechanism (**Table. 1**), plant incorporated protectants (PIPs) (Genome of the plants modified to produce pesticidal substances e.g. Bt pesticidal protein), and RNA interference pesticides (EPA, 2012).

Table.1: Examples of some commercially available biochemical pesticides

TYPE OF PESTICIDE	ACTIVE INGREDIENT	PRODUCT NAME	TARGET	CROP
INSECTICIDE	Azadirchtin	**AZATIN XL**	Aphids, Thrips, Whitefly, Leafhoppers, Weevils,	Vegetables, fruits, herbs, and ornamental crops
HERBICIDE	Citronella oil	**BARRIER H**	Ragwort	Grass land
NEMATICIDE	*Quillaja saponaria*	**NEMA- Q**	Plant Parasitic Nematodes	Vineyards, orchards, field crops, ornamentals and turf
ATTRACTANT	(E,E)-8, 10 - dodecadien-I-oI	**EXOSEXCM**	Codling moth	Apple and pears
ATTRACTANT	Citronellol	**BIOMITE**	Tetranychid mites	Apples , cucurbits, grapes, hops, nuts, pears, stone fruits, nursery and ornamental crops

MICROBIAL PESTICIDES

Among the three categories of biopesticides over 90% are based on microbes such as bacteria, fungi and viruses. The microbial formulations that are mass produced, registered, marketed and applied inundatively like chemical pesticides are termed as microbial pesticide. Based on pest of interest the microbial pesticides are named as bioinsecticides when used against arthropod pests (insects), biofungicides when used against crops fungal pathogens, bioherbicides when used against weeds and bionematicides when used to target plant parasitic nematodes. Since microorganism pathogenic to pest occurring naturally, the microbial pesticides are usally non toxic to humans, domestic animals and plants. In addition, they are non pathogenic to non target pest owing to their high degree of specificity (Aneja, 2000). According to Thakore (2006), for all crop types bacterial biopesticide claim about 74% of the market followed by fungal biopesticides 10%, viral biopesticides 5%, predator biopesticides 8% and others 3% around the world.

Bioinsecticides

The idea of biological control of insect pests was originally given by Metchnikoff and Pasteur in 1882. During the 1940s, the investigations on the microbial control of insects pests began to advance rapidly and the mass production and formulations of microbial preprations as microbial insecticides were initiated in 1950s. During the past 50 years several microbial pesticides have been developed and commercialized around the globe as summarized in the **table 2**.

Biofungicides

Biofungicides are formulations of living organisms that are used to control the activity of plant pathogenic fungi and bacteria. The concept of biofungicides is based upon observations of natural processes where beneficial microorganisms, usually isolated from soil, hinder the activity of plant pathogens. Biocontrol microorganisms are free-living fungi, bacteria, or actinomycetes that are active in root, soil, and foliar environments. These microorganisms produce a wide range of antibiotic substances, parasitize other fungi, compete with other fungi, and induce localized or systemic resistance to a variety of plant pathogens. The use of composts and suppressive growing medium, which both contain living microorganisms, to ameliorate disease is another example of this disease management option. The biofungicidal agents show its efficiency on the following criteria:

i) **Parastitism -** Parasitism, the ability of species to attack and consume plant pathogens, has been well studied. Mycoparasitism of biocontrol microorganisms includes directed growth, contact and binding, coiling of hyphae around the host fungus, penetration and degradation. Production of cell wall degrading enzymes is an essential part of biocontrol process.

ii) **Antibiosis -** Antibiosis occurs when one microorganism produces molecules that directly affect other organisms negatively by toxicity or growth inhibition. These compounds are called antibiotics and are commonly produced by a wide range of soil dwelling microorganisms in the course of their growth.

iii) **Rhizosphere Competence -** The most successful of the strains of biocontrol microorganisms exhibit rhizosphere competence, the ability to colonize and grow in association with plant roots.

Iv) **Plant Growth Promotion -** Beneficial root-colonizing microorganisms promote plant growth and productivity. Many resistance-inducing fungi and bacteria promote both root and shoot growth in the absence of disease causing fungi.

v) **Inducing Metabolic Changes -** Biocontrol microorganisms have the ability to induce metabolic changes in plants that increase their resistance to a wide range of plant pathogenic microorganisms (fungi and bacteria). Systemic Acquired Resistance (SAR) improves the plant response to pathogen attack by priming the metabolism of plant defense compounds.

Control of *Heterobasidion* (Fomes) *annosum* with *Peniophora* (*Phlebia*) *gigantea* was the first successful example of biocontrol of a plant pathogen by an antagonist devised by Rishbeth in England in 1963 (Rishbeth, 1975). The commercial preparation of *P. gigantea* in England consists of dehydrated tablets containing $1x10^7$ viable spores. In the greenhouse industry, biofungicides are applied preventively to growth media or as a seed treatment for disease control and can be as effective as chemical fungicides. Biofungicides are safer for growers, more persistent, and less expensive. When applied as seed treatment, biofungicides increase root development in a number of plants and improve drought resistance. Improvements in plant growth result from effects on soil microflora and direct effects on the plant. Biofungicides can also improve nutrient uptake (copper, phosphorous, iron, and manganese). The summary of biofungicides developed and commercialized around the globe is given in **table-3.**

Bioherbicides (Mycoherbicides)

The number of research reports on bioherbicide development has increased tremendously since the early 1980s. Both the number of weeds targeted for control and the number of candidate pathogens studies has increased. Practical registered or unregistered uses of bioherbicides have also increased worldwide (**Table-4**). Likewise, the number of US patents issued for the bioherbicidal use of fungi and their technology have increased, perhaps foretelling an increased reliance on bioherbicides in the future (El-Sayed, 2005). The most commercial biological weed control products researched and registered all over the world have been based on formulations of fungal species, however, few have been successful in the long term.Three genera of fungi namely *Colletotrichum* spp., followed by *Chondrostereum* spp. and *Fusarium* spp. have received the majority of attention as bioherbicide candidates (Aneja, 2014; Bailey, 2014). A number of bacteria have also been investigated as potential

Table 2. Commercially available bacteria, fungi and virus based bioinsecticides in the United States of America, Europe, Japan and India*

BIOCONTROL AGENTS	COUNTRY	PRODUCT NAME	AGAINST PESTS
Bacillus popilliae	**UNITED STATES OF AMERICA**	DOOM-Milky Spore Powder	Japanese beetle grubs
B. sphaericus Serotype H5ab strain 2363 ATCC1170		VectoLex	Mosquito and blackflies
B. thuringiensis subsp. *aizawai* NB 200		Florbac	Moth larvae
B. thuringiensis subsp. *israelensis*		BMP	Mosquito and blackflies
B. thuringiensis subsp. *israelensis* EG2215		Gnatrol /Aquabac	Mosquito, flies
B. thuringiensis subsp. *aizawai* delta-endotoxin in killed *P. fluorescens*		M-Trak	Colorado potato beetle
B. thuringiensis subsp. *aizawai* GC-91		Agree WG	*Plutella xylostella* (Diamond black moth)
B. thuringiensis subsp. *kurstaki*		Thuricide Forestry / Wilbur-Ellis BT 320/ Dust /Dipel/Deliver/ Biobit HP/ Foray/ Javelin WG/ Green Light / Hi-Yield Worm Spray/ Ferti-Lome /Bonide / Britz BT/ Worm Whipper / Security Dipel Dust/	Lepidopteran larvae
B. thuringiensis subsp. *kurstaki* BMP 123		BMP123	Lepidopteran larvae
B. thuringiensis subsp. *kurstaki* EG2348		Condor	Lepidopteran larvae
B. thuringiensis subsp. *tenebrionis*		Novodor	Colorado potato beetle
B. thuringiensis subsp. *kurstaki* EG7826		Lepinox WDG	Lepidopteran larvae
Beauveria bassiana 447		Baits Motel Stay-awhile	Ants
B. bassiana ATCC 74040		Naturalis L	Various insects
B. bassiana GHA		Mycotrol ES /Mycotrol O / Botanigard 22WP / BotaniGard ES	Various insects
B. bassiana HF23		bal Ence	Housefly
Metarhizium anisopliae F52		Tick-Ex	Ticks and grubs
Paecilomyces fumosoroseus Apopka 97		PFR-97	Whitefly and thrips
Nosema locustae		Nolo-Bait / Semaspore Bait	Grasshopper and crickets
Anagrapha falcifera NPV		CLV-LC	Lepidopteran larvae
Cydia pomonella GV		CYD-X	Virus codling moth
Gypsy moth NPV		Gypchek	Gypsy moth
Heliothis zea NPV		ELCAR / GemStar	Cotton bollworm, tobacco budworm
Plodia interpunctella GV (Indian meal moth)		FruitGuard	Indian meal moth
Mamestra configurata NPV (107308)		Virosoft	Bertha armyworn
Spodoptera exigua NPV		Virus Spod-X	Beet armyworm
Saccharomyces cerevisiae		Bull Run	Fly attractant
Bacillus thuringiensis subsp. *aizawai* GC-91	**EUROPE**	Turex	Lepidoptera pest
B. thuringiensis subsp.*israelensis* AM65		VectoBac	Sciaridae
B. thuringiensis subsp. *israelensis* EG2215		Gnatrol /Aquabac	Mosquito, flies
B. thuringiensis subsp. *kurstaki* HD-1		Dipel WP	Lepidopteran larvae
B. thuringiensis subsp. *kurstaki* ABTS 351,PB54, SA11 &12 , and EG 2348		Batic / Delfin	Lepidopteran larvae
B. thuringiensis subsp. *kurstaki* BMP123		BMP 123 / Prolong	Lepidoptera pest
B. thuringiensis subsp. *tenebrionis* NB176		Novodor	Coleoptera pest
Beauveria bassiana ATCC 74040		Naturalis L	Mites, Whitefly and thrips
B. bassiana GHA Fungus		Botanigard	Whitefly, aphids and thrips

Contd...

Table 2 continued...

BIOCONTROL AGENTS	COUNTRY	PRODUCT NAME	AGAINST PESTS
Lecanicillium muscarium (Ve 6) (= *Verticillium lecanii*)	**EUROPE**	Mycotal / Vertalec	Whiteflies, thrips, aphids except *Macrosiphoniella sanborni –Chrysanthemum* aphid
P. fumosoroseus Apopka 97		Preferal WG	Green house Whiteflies
P. fumosoroseus Fe9901		Nofly	Whiteflies
Adoxophyes orana BV-0001GV		Capex	Summer fruit tortrix (*Odoxophyes orana*)
Cydia pomonella GV		BioTepp	Codling moth (*C. pomonella*)
Spodoptera exigua NPV		Spod-X GH	*Spodoptera exigua*
B. thuringiensis subsp. *kurstaki*	**JAPAN**	Toarowaa / Esmark / Guartjet / Dipol / Tuneup/ Fivestar/ Biomax/ DF	Lepidopteran larvae
B. thuringiensis subsp. *aizawai*		Quark / Xen Tari / Florbac / Sabrina	Lepidopteran larvae
B. thuringiensis subsp. *aizawai* + *kurstaki*		Bacilex	Lepidopteran larvae
Beauveria bassiana		Botanigard	Whitefly, diamond back moth and thrips
Lecanicillium longisporum		Vertalec	Aphids
Paecilomyces fumosoroseus		Preferd	Whiteflies and aphids
P. fumosoroseus Fe9901		Nofly	Whiteflies
Adoxophyes orana GV + Homona magnanima GV		Hamaki-Tenteki	*Odoxophyes honmai* and *Homona magnanima*
Steinernema carpocapsae		Bio Safe	Weevils, back cut worm, peach fruit moth
Bacillus thuringiensis subsp. *israelensis*	**INDIA**	Tacibio / Technar	Lepidopteran pests
B. thuringiensis subsp. *kurstaki*		Bio-Bart /Biolep /Halt / Taciobio-Btk	Lepidopteran pests
Beauveria bassiana		Myco-Jaal / Biosoft /ATEC Beauveria /Larvo-Guard / Biorin / Biolarvex / Biogrubex/ Biowonder / Vera / Phalada 101B / Bioguard / Bio-power	Coffee berry borer, diamondback moth, thrips, grasshoppers, whiteflies, aphids, codling moth
Metarhizium anisopliae		ABTEC /Meta –Guard Biomet /Biomagic Meta/ Sun Agro Meta Bio-Magic	Coleoptera and Lepidoptera, termites, mosquitoes, leafhoppers, beetles, grubs
Paecilomyces fumosoroseus		Nemato-guard / Priority	Whitefly
P. lilacinus		Yorker/ABTEC / / Paecil / Paceilomyces / Pacihit / ROM biomite /Bio-Nematon	Whitefly
Verticillium lecanii		Verisoft / ABTEC / Ecocil/ Verticillium /Vert -Guard Bioline / Biosappex / Versitile / Phalada 107V / Biovert Rich /ROM Verlac / ROM Gurbkill /Sun Agro Verti / Biocatch	Whitefly, coffee green bug, homopteran pests
Helicoverpa armigera NPV		Helicide / Virin-H / Helocide / Biovirus-H /Helicop / Heligard /	*H. armigera* (Cotton bollworm)
Spodoptera litura		Spodocide / Spodoterin Spoddi-cide /Biovirus-S	*S. litura* (Oriental leaf worm)

* Modified form Mishra *et al.*, 2015

biological weed control agents?. Of these, *Xanthomonas campestris* and *Pseudomonas fluorescens* attracted the attention most. Biological weed control using bacteria has been suggested to have several advantages over the use of fungi, including more rapid growth of the bioherbicide agents (Johnson *et al*., 1996), relatively simple propagation requirements (Li *et al*., 2003), and high suitability for genetic modification through either mutagenesis or gene transfer (Johnson **et al**., 1996).The bacteria *Xanthomonas campestris* strain JT-P482 has received much of the attention as a promising biocontrol agent in Japan for control of annual bluegrass (*Poa annua*) under the product name CAMPERICO (Imaizumi *et al*., 1997; Tateno, 2000). The production of extracellular metabolites with phytotoxic

Table: 3. A summary of commercial products used as biofungicides around the globe*

BIOCONTROL AGENTS	PRODUCT NAME	TARGET PATHOGENS	CROPS
Trichoderma harzianum	**PLANT SHIELD, ROOT SHIELD, T-22 PLANTER BOX**	*Cylindrocladium*, *Fusarium Rhizoctonia*, *Pythium*, *Thielaviopis*	Most greenhouse ornamentals, vegetable transplants.
Gliocladium virens GL-21	**SOILGARD**	*Rhizoctonia*, *Pythium*	Most greenhouse ornamentals, vegetable transplants.
Gliocladium catenulatum JII446	**PRESTOP** WP	*Botrytis*, *Rhizoctonia*, *Pythium*, *Phytophthora*, *Fusarium*, *Verticillium*	Most greenhouse ornamentals, vegetable transplants.
Agrobacterium radiobacter K84	**GALLTROL**	*Agrobacterium tumefaciens*	Ornamental nursery stock. Soil treatment.
Bacillus subtillis QST 713	**CEASE**	*Rhizoctonia*, *Pythium*, *Phytophthora*, *Fusarium*	Most greenhouse ornamentals, vegetable transplants.
Bacillus subtillis GB03	**COMPANION** (LIQUID)	Leaf spots, Powdery mildew, *Botrytis*, bacterial diseases, *Rhizocotonia*, *Pythium*, *Phytophthora*	Most greenhouse ornamentals, vegetable transplants.
Bacillus subtilis	**EPIC** (Dry powder)	*Fusarium spp.*, *Rhizoctonia solani*, *Alternaria* spp., *Aspergillus* spp.	Cotton and legumes
Bacillus subtlis	**KODIAK, KODIAK HB, KODIAK A.T** (Dry powder)	*Rhizoctonia solani*, *Alternaria* spp., *Aspergillus* spp., *Fusarium spp.*,	Cotton and legumes
Pseudomonas cepacia	**INTERCEPT**	*Fusarium spp.*, *Rhizoctonia solani*, *Pythium*,	Maize, vegetables, cotton
Coniothryium minitans	**CONTANS** WG	*Sclerotinia sclerotiorum*, *S. minor*	Most greenhouse ornamentals, vegetable transplants & herbs. Soil treatment.
Streptomyces griseoviridis	**MYCOSTOP** (Dry powder)	*Botrytis*, *Rhizoctonia*, *Pythium*, *Phytophthora*, *Alternaria*	Most greenhouse ornamentals, vegetable transplants.
Reynoutria sachalinensis	**REGALIA**	*Botrytis*, Leaf Spots, Powdery mildew, bacterial diseases, *Fusarium*, *Rhizoctonia*, *Pythium*, *Phytophthora*, *Verticil lium*	Herbs and spices. Soil treatment. Plant health promoter.
Streptomyces lydicus	**ACTINOVATE**	Powdery mildew, Downy mildew, *Botrytis*, *Rhizoctonia*, *Pythium*, *Phytophthora*	Most greenhouse ornamentals, vegetable transplants.
Myrothecium verrucaria	**DITERA** (Wettable powder)	Root knot, citus cyst, stubby root, lesions and burrowing nematodes	Fruit vegetables and and ornamental crops, turf
Fusarium oxysporum (non pathogenic)	**FUSACLEAN** (spores)	*Fusarium oxysporum*	Asparagus, basil, carnation, tomato
Psudomonas fluorescens	**PHAGUS** (Bacterial Suspension)	*Pseudomonas tolassii*	*Agaricus* spp.; *Pleurotus* spp.

****Source:*** The UMass Center for Agriculture, Food and the Environment, 2016 ; Burges, 1998)

Table 4. Examples of commercial bioherbicides and type of formulation used globally

S. No.	BIOCONTROL AGENTS	PRODUCT NAME	FORMULATION TYPE	TARGET WEED	YEAR OF REGISTRATION & COUNTRY
1.	*Acremonium diospyri*	**ACREMONIUM DIOSPYRI**	Conidial suspension	Persimmon (*Diospyros virginiana*) trees in rangelands	**1960 Canada**
2.	*Colletotrichum gloeosporioides* f. sp. *cuscutae*	**LUBAO**	Conidial suspension	Dodder (*Cuscata chinesis* and *C. australis*) in soybeans	**1963 China**
3.	*Phytophthora palmivora(P. citrophthora*)	**DEVINE**[R]	Liquid spores suspension	Milkweed vine (*Morrenia odorata*)	**1981 USA**
4.	*Colletotrichum gloeosporioides* f.sp. *aeschynomene*	**COLLEGO™ (LOCKDOWN™)**	Wettable powder	Northern joint-vetch (*Aeschynomene virginica*)	**1982 USA**
5.	*Alternaria cassia*	**CASST™**	Solid	Sickle-pod and coffee senna (*Cassia* spp.)	**1983 USA**
6.	*Cercospora rodmanii*	**ABG-5003**	Wettable powder	Water hyacinth (*Eichhornia crassipes*)	**1984 USA**
7.	*Puccinia canaliculata*	**DR. BIOSEDGE**	Emulsified suspension	Yellow nutsedge (*Cyperus esculentus*)	**1987 USA**
8.	*Colletotrichum coccodes*	**VELGO**[R]	Wettable powder	Velvet leaf (*Abutilon theophrastus*)	**1987 Canada**
9.	*Colletotrichum gloeosporioides* f.sp. *malvae*	**BIOMAL**[R]	wettable powder in silica gel	Round-leaved mallow (*Malva pussila*)	**1992 Canada**
10.	*Cylindrobasidium leave*	**STUMPOUT™**	Liquid (oil) suspension	Turf grass (*Poa annua*) in golf courses, *Acacia* sp.	**1997 South Africa**
11.	*Chondrostereum purpureum*	**BIOCHON™**	Mycelial suspension in water	Woody plants Blackberry weed (*Prunus serotina*)	**1997 Netherlands**
12.	*Xanthomonas campestris* pv *poae*	**CAMPERICO™**		Turf grass (Poa annua) in Golf courses	**1997 Japan**
13.	*Colletotrichum acutatum*	**HAKATAK**	Conidial suspension **Granular Dry Conidia**	*Hakea gummosis* & *H. sericea* in native vegetation	**1999 South Africa**
14.	*Puccinia thlaspeos*	**WOAD WARRIOR**	Powder	Dyers woad (*Isastis tinctoria*) in farms, rangeland, waste areas & roadsides	**2002 USA**
15.	*Chondrostereum purpureum*	**MYCOTECH™ PASTE**	Paste	Deciduous tree species	**2002/2005 Canada**
16.	*Chondrostereum purpureum*	**CHONTROL™ (ECOCLEAR™)**	Spray emulsion & paste	Alder, aspen and other hardwoods	**2004/2007 Canada**
17.	*Alternaria destruens*	**SMOLDER**[R]	Conidial suspension	Dodder species	**2005 USA**
18.	*Sclerotinia minor*	**SARRITOR**	Granular	Dandelion (*Taraxacum officinale*) in lawns/turf	**2007 Canada**
19.	*Fusarium oxysporum* f. sp. *stigae*	**STRIGA**	Solid, Dried Chlamydospores+ Arabic gum	*Striga hermonthica* and *S. asiatica*	**2008 Africa**
20.	Tobacco mild green mosaic virus	**SOLVINIX™**	Wettable powder /Foliar spray suspension	Soda apple (*Solanum viarum)*	**2009 Florida**
21.	*Lactobacillus* spp. *Lactococcus* spp.	**ORGANO-SOL**	Liquid	Broadleaved weeds	**2010 Canada**
22.	*Phoma macrostoma*	**Formulation Product name not Specified**	Granules composed of mycelial fragments and flour	Broadleaved weeds	**2011 Canada/USA**
23.	*Streptomyces* spp.	**MBI-005 EP**		Broadleaved weeds	**2012 USA**
24.	*Gibbago trianthemae*	**GIBBATRIANTH**	Liquid Conidial Suspension+Surfactant	*Trianthema portulacastrum* (Horse purslane)	**2014 India**

*Source: Aneja, 2014

effects has also been observed in an additional *Pseudomonas fluorescens* strain, referred to as BRG100, which has been recognized to have suppressive activity on the *Setaria viridis* grassy weed (green foxtail) (Quail *et al*., 2002; Caldwell *et al.*, 2012).

Most importantly, the crop protection technologies were greatly emphasised at the annual Agrow Awards held on September 17th, 2016 at London. This event recognizes innovation from all over the world in fields such as formulation, packaging and crop protection. The 2015 recipient of Agrow's award for best new biopesticide is SolviNix, a pesticidal application developed by BioProdex of Gainesville, Florida SolviNix, approved by the FDA in April of this year, provides a bioherbicide which combats tropical soda apple (*Solanum viarum*), a weed which can crowd out other plants and livestock feed (Brachmann, 2015). In select cases, viruses that affect weed species have also been considered as bioherbicide candidates. Viruses have been suggested to be inappropriate candidates for inundative biological control due to their genetic variability and lack of host specificity (Kazinczi *et al.*, 2006)

Presently, approximately 24 bioherbicide have been registered around the globe as given in **Table-4**. 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 (Aneja *et al*., 2014; Dagno *et al*., 2012; Harding and Raizada, 2015). Interestingly, maximum commercially produced formulations are in liquid state. The research findings of Auld *et al* (2003) revels that the formulation of a bioherbicide ideally results in a product that has low cost, long shelf-life, ease of application and efficacy. Formulation persists as a constraint to commercial development of many potential bioherbicides often because dew dependence in fungi limits their efficacy under dry-land conditions. This has not been a problem with several commercial bioherbicides because they are used in irrigated systems or applied as wound inoculations. Thus, reduction in dew dependence is a principal aim in the formulation of many potential bioherbicides. Solid formulations typically must be able to survive in the field and await suitable conditions before becoming activated. Liquid formulations have the potential to produce infections soon after application provided they remain moist on the target plant surface. Several attempts have been made to improve the water-holding capacity in liquid formulations.

Bionematicides

Another class of biocontrol agent is entomopathogenic nematodes (EPN) that are used to manage pests like weevils, gnats, white grubs and various species of the insects of *Sesiidae* family. These fascinating organisms control the population of insects in cryptic habitats (such as soil-borne pests and stem borers). Commonly used nematodes in pest management belong to the genera *Steinernema*, *Heterorhabditis* and *Phasmarhabiditis* which attack the hosts as infective juveniles (Kaya and Gaugler,1993; Koppenhofer and Kaya, 2002). Kaya and Gaugler (1993) reported that infective juveniles (IJS) are free-living organisms which enter the insect through mouth, spiracles or cuticle and anus. The nematodes can complete up to three generations within the host, after which the IJs leave the cadaver to find the new hosts. Nematodes that have been successfully used as a bionematicides are *Steinernema carpocapsae*, *S. riobravis*, *S. glaseri*, *S. scapterisci*, *Heterorhabditis bacteriophora*, *H. megidis* and *Phasmarhabditis hermaphrodita*. Some commercially available bionematicides around the world are listed in **Table-5.**

Table 5. Examples of commercially available bionematicides

BIOCONTROL AGENTS	TARGET PESTS	PRODUCT NAME	Dealer/Company
Steinernema carpocapsae	Weevils, black cutworm, common cutworm, peach fruit moth	**BIO SAFE**	SDS Biotech Co. Ltd.
S. glaseri	White grubs, weevils, blackcutworm, blue grass webworm, lawn grass cutworm	**BIO TOPIA**	SDS Biotech Co. Ltd.
S. feltiae	Vine weevils, fungus gnats, sciarid flies and soil insects	**ENTONEM** **EXHIBIT SF-WDG** **NEMASYS** **NEMA-PLUS** **OTIENEM** **SCIA-RID** **X-GNAT** **NEEMA SHIELD** **GNAT NOT** **SCAN MASK**	Koppert Novartis BCM Becker Underwood e-nema GmbH Biobest Koppert Certis Biocontrol Inc Integrated Biocontrol System Biologic Co
S. riobravis	Citrus weevils	**BIOVECTOR 355** **DEVOUR**	Certis
S. scapterisci	Mole crickets	**NEMATAC S**	Becker Underwood Inc
Heterorhabditis bacteriophora	Lepidopteran larvae, turf and Japanese beetles and soil insects	**CRUISER*** **HETEROMASK** **NEMA-BIT** **NEMA-TOP/-GREEN** **LAWN PATROL** **GRUBSTAKE** **LARVANEM** **TERRANEM**	Ecogen BioLogic BIT e-nema Hydro-Gardens Integrated Biocontrol Systems Koppert
H. megidis	Black vine weevils and soil insects	**LARVANEM** **DICKMAULRUSSLER-NEMATODEN**	Koppert Bio Syst. AndermattBiocontrol AG
Phasmarhabiditis hermaphrodita	Slugs	**NEMASLUG**	Becker Underwood Inc

*Modified from Koul, 2011

CURRENT STATUS OF BIOPESTICIDES

The total world production of biopesticides is over 3000 tonnes per year and their use is increasing steadily by 10% every year (Gupta and Dixit, 2010; Kumar and Singh, 2015). There are about 1400 biopesticidal products prepared and sold globally (Marrone, 2007). EPA indicates that over 200 products are sold in the US market compared to only 60 similar products available in the European Union (EU). More than 225 microbial biopesticides are manufactured in the 30 OECD countries. The NAFTA countries (the USA, Canada and Mexico) use about 45% of the biopesticides sold, while Asia lacks behind with the use of only 5% of the biopesticides sold globally (Bailey *et al*., 2010; Hubbard *et al*., 2014).

The rapid growth in the biopesticide market is based on the advantages associated with such products that includes; inharently less harmfull and less environmental load; affecting only one specific pest or in some cases a few target pests; often effective in small quantities; often decompose or die quickly thereby resulting in lower exposure to the biota thus avoiding the pollution problems; non toxic to humans. Moreover, when used as a component of Integrated Pest Managemet (IPM) programms biopesticides can greatly decrease the use of chemical pesticides while achieving the same level of crop yield.

BIOPESTICIDE MARKET

Based on the BBC report of 2010, the global pesticide market was valued as 40 billion US$ in 2008 and this figure increase to nearly 43 billion$ in 2009 as is expected to grow at a compound annual growth rate (CAGR) of 3.6% to reach 51 billion$ in 2014. Biopesticide market represents a strong growth area in global pesticide market which is expected to grow at 15.6% CAGR from 1.6 billion $ in 2009 to 3.3 billion $ in 2014 (**Fig.1**).

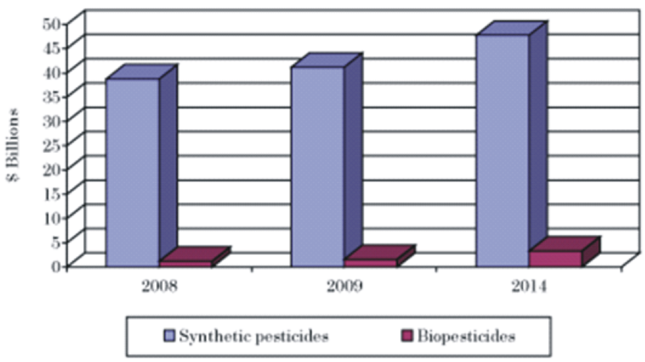

Fig.1. Trends of global production of synthetic pesticides Vs biopesticides between 2008 and 2014 (Billion$)

Sinha and Biswas (2008) reported that regionwise North America consumes the largest share (40%) of the global biopesticide production followed by Europe and Oceanic countries accounting for 20% each. Trend of Biopesticides consumption in India has shown dramatic increase in uses over the time which stood at 1920 metric tonne in 2005-2006 (**Fig.2**.) (Gupta and Dixit, 2010).

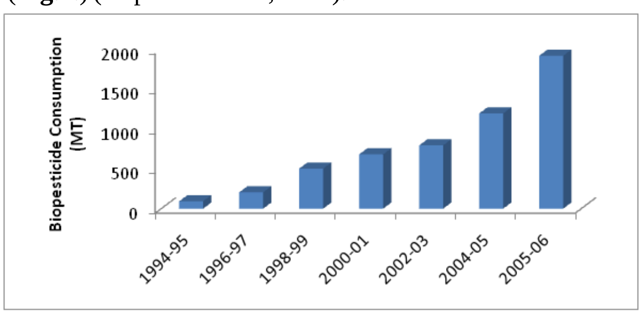

Fig .2. Trend of biopesticide consumption in India between 1994 and 2006

This figure represents only 2.89 % of the over all pesticide market in India and is expected to exhibit an annual growth rate of 2.3% in the coming years (Thakore, 2006). A total 12 types of biopesticides have been registered under the insecticide act, 1968 in India (**Table 6**). Of theses neem based pesticide, *Bacillus thuringiensis*, NPV and *Trichoderma* are the major biopesticides produced and used in India (Sinha and Biswas, 2008; Gupta and Dixit, 2010).

MAJOR CHALLENGES AND CONSTRAINTS

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

S. No.	Name of the biopesticide
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	*Beauveria bassiana*
9	NPV of *Helicoverpa armigera*
10	NPV of *Spodoptera litura*
11	Neem based pesticides
12	*Cymbopogon*

Dependence on synthetic pesticides and their indiscriminate use caused several adverse effects including pest resistance, soil fertility, water quality, outbreak of secondary pests and pesticide residues in the products (Al Zaidi *et al.*, 2011). Undoubtedly, biopesticides play vital role in controlling the desirable pests and gaining interest among the population with advantages like non toxic mechanism, eco-friendly nature, efficacy and suitability in the Integrated Pest Management programmes. Since, biopesticide is produced usually with live microbe/s, utmost attention and care is required from the beginning of the developmental step till the end use. The production and utilization of biopesticide are increasing at a maximum pace around the world. The few disadvantages of using biopesticides like slow effect, lack of persistence and wide spectrum activity, rapid degradation by UV lights, poor water solubility and their availability seems to be the main hurdles in the development and commercialization of any biopesticides. However, the lack of awareness about biopesticides benefits, knowledge about biopesticide products and confidence in farmers are the chief constraints in the pace of the development of biopesticides. Many farmers stopped the use of biopesticides because of unreliable supply and inconsistency in performance (Alam, 2000). Arora *et al.* (2010) stated that lack of faith in the use and performance of biopesticides was found to be one of the key factors responsible for their lagging behind. The countries like the United States, Canada and Mexico use about 45% of the total biopesticide sold, while Asia lack behind with the use of only 5% of biopesticides sold in the market around the world (Bailey *et al.*, 2010). The unclear regulatory policies in many countries on the development and use of genetic engineering in the production of biopesticides also a major impediment to the application of biotechnological applications to biopesticides. The registration processes of biopesticides often possess a particular challange to the developers.

The viral pesticides as disease producing agents have some inherent advantages over conventional insecticides including

- narrow host range, infecting only closely related species of target insect, and most importantly eco - friendly. Inspite these, various problems are encountered with their development and marketing. The major problems associated with viral biopesticide are production conditions and public acceptance. These include the expenses and time involved in carrying out tests as per government rules and regulations. Secondly, its cultivation on live host, tissue or cell line culture. Development of tissue culture laboratory for the same again needs ethical clearance from the government department (Lapointe *et al*., 2012). Production of virus products in insects is more complicated and less precise than chemical pesticides.

According to Ravensberg (2011) commercialization is the last and most difficult step in the development of a microbial product. The most critical factors faced during development are product cost and time to market. Costs amount to US$14 - 21 million for a new entrepreneur and the time to market including registration is no less than 5-7 years. Therefore, to examine all these critical factors in the successful commercialization of microbial pest control products is essential in the developmental process of a product.

CONCLUSION

The National Farmer Policy 2007 has strongly recommended the exploration of biopesticides to control pests in eco-friendly manner. Biopesticide research is young and evolving and required more attention and reliability. A deep research is required in the development of biopesticides including screening of potential control agent/s, formulation, delivery and commercialization. Inspite of this people in general and agriculturists in particular must be educated and skilled about the product handling and use of such control measures. Biopesticides are attracting global attention as safer, eco-friendly approach to manage pest populations such as weeds, plant pathogens and insects while posing less risk to animals, human beings and the environment. As environmental safety is a global concern, we need to create awareness among the farmers especially in the developing countries, manufacturers, government agencies, policy makers and the common man to switch-over to biopesticides for pest management requirements.

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