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Present Status and Future Prospects of Bio-Agents in Agriculture

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ABSTRACT

Managing agricultural production systems on a sustainable basis is one of the most critical challenges for the future of humanity as the world population is increasing exceptionally. Concepts of modern technologies in agricultural systems have given an important role for the improvement of agricultural productions e.g. crop yield, livestock production, aquaculture production, and sustainable agriculture, in order to maintain food security. Protection of crops against plant diseases, have an evident role to play to meet the rising demand for food quality and quantity (Strange and Scott, 2005). Approximately, direct yield losses caused by pathogens, animals, and weeds, are altogether responsible for losses ranging between 20 and 40 % of global agricultural productivity (Oerke, 2006). Therefore, in order to meet the growing food demand, about 15–20 times increase in the use of synthetic pesticides will be required (Oerke, 2006) but the excessive use of synthetic pesticides is no longer sustainable and causes land, air and water contamination and also responsible for causing resistance development in pathogens and insects as well as adverse impacts on natural enemies and humans (Birch *et al.*, 2011). Due to strong consumer demands to address food security and environmental safety has resulted in the lesser use of synthetic pesticides, the lowering of maximum residue limits and changes in the regulatory environment that favour more environmentally safe control options. Thus there is need to switch for more environmentally safe and ecologically sound pest control methods such as bioagents/biopesticides.

Keywords

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Introduction

The global population is projected to reach 8.5 billion by 2030, 9.7 billion by 2050 and exceed 11 billion in 2100 (UN. World Population Prospects, 2011). There is continued need for pest management in agriculture, with pressure continuously increasing on agriculture to achieve higher yield from limited or even lesser land (UN.

World Population Prospects, 2011). Pests (which include invertebrates, pathogens and weeds) are estimated to cause between 27% and 42% losses in production for major crops around the world, but this would rise to a staggering 48–83% without crop protection (Oerke, 2006). Therefore, in order to meet the growing food demand, about 15–20 times increase in the use of synthetic pesticides will be required (Oerke, 2006) but the excessive

use of synthetic pesticides is no longer sustainable and causes land, air and water contamination and also responsible for causing resistance development in pathogens and insects as well as adverse impacts on natural enemies and humans (Birch *et al.*, 2011). Due to strong consumer demands to address food security and environmental safety has resulted in the lesser use of synthetic pesticides, the lowering of maximum residue limits and changes in the regulatory environment that favour more environmentally safe control options. Thus there is need to switch for more environmentally safe and ecologically sound pest control methods such as bioagents/biopesticides. Biopesticide is a term that has been applied with a narrow focus on preparations containing living microorganisms, through to a broader definition that encompasses botanical compounds and semiochemicals (e.g. pheromones) (Kiewnick, 2007). In this chapter, we are restricted to microbial pest control agents (bacteria, viruses, fungi, protozoa and nematodes) and/or bioactive compounds (such as metabolites) produced directly from these microbes, which are used to suppress populations of pests, including insects, pathogens and weeds. Biopesticides are the formulations of bioagents in a form which keep the organism at higher count and viable for their introduction or application in the field (Van, 2012).

Many microorganisms in biopesticides also deliver a number of benefits beside virulence to a target pathogen. For example, *Trichoderma* species are known to enhance the uptake of soil macro and micro nutrients by plants (Harman, 2011) and specific isolates can deliver substantial plant growth benefits in the absence of a disease (Clouston. *et al.*, 2010). Entomopathogenic fungi can also have antagonistic activity against plant pathogens attacking the same crop (Ownley *et al.*, 2010).

There is recent evidence that endophytic microorganisms which provide protection against diseases, can also provide abiotic stress (drought and salt) tolerance attributes to certain crops (Shukla *et al.*, 2012; Rawat *et al.*, 2011). Benefits in addition to pest control can be an important selection criterion in screening programs to choose commercially attractive biocontrol isolates (Köhl *et al.*, 2011) and open up a significant opportunity for marketing biopesticides as products with an added value. The interest in biopesticides is based on the advantages associated with such products which are: (i) inherently less harmful and less environmental load, (ii) designed to affect only one specific pest or, in some cases, a few target organisms, (iii) often effective in very small quantities and often decompose quickly, thereby resulting in lower exposures and largely avoiding the pollution problems and (iv) when used as a component of Integrated Pest Management (IPM) programs, biopesticides can contribute greatly. Besides, biopesticides have the following benefits

Factors	Benefits of biopesticides
1. Cost effectiveness	Costlier but reduced number of applications
2. Persistence and residual effect	Low, mostly biodegradable and self perpetuating
3. Knockdown effect	Delayed
4. Handling and Bulkiness	Bulky; Carrier based;
5. Pest resurgence	Easy; Liquid formulation
6. Resistance,	Less
7. Effect on beneficial flora	Less prone
8. Target specificity	Less harmful on beneficial
9. Waiting time	Mostly host specific
10. Nature of control	Almost nil
11. Shelf life	Preventive
	Less

Negative impact of chemicals has brought into focus the use of safer and effective alternative such as bioagents/biopesticides. Various microorganisms are currently being

utilized as bioagents are *Trichoderma* spp., *Pseudomonas fluorescence*, *Bacillus* spp., *Ampelomyces quisqualis*, *Agrobacterium radiobacter*, nonpathogenic *Fusarium*, *Coniothyrium*, and atoxigenic *Aspergillus niger* (Singh. *et al.*, 2014 and Keswani *et al.*, 2015). India has huge potential for the growth of industry as it losses crops of worth US\$ 9259 million every year due to low consumption of pesticides in the country (<https://www.mordorintelligence.com/>).

Biopesticides are derived from microorganisms and other natural sources, and are an eco-friendly alternative to the synthetic pesticides. As next generation pesticides, biopesticides are gaining popularity in India.

Due to presence of higher pesticides residues in food crops, specifically on grains and increasing pest resistance, developed countries are posing strict regulations on use of some synthetic pesticides, which will affect the use of synthetic pesticides and will promote the use of biopesticides in the region. Other factors driving the growth of the market are the ecofriendly nature of biopesticides, constructive public support policies, increasing public awareness and lesser development of pest resistance.

The significance of biopesticides in integrated pest management (IPM) system has also increased its popularity in India. However, the domestic market has been plagued by factors hindering the potential growth of biopesticides, such as non-availability, lesser reach and continuing disappearance of mixed/multiple cropping that adversely affects demand for biopesticides.

Historical perspective

Historically, biopesticides came into existence because of environmental pollution concerns

coupled with chemical pesticides. It is expected that plant extracts were probably the most primitive agricultural biopesticides, use of nicotine to control plum beetles was recorded as early as the 17th century. Use of white-muscadine fungus (*Beauveria bassiana*) to cause an infectious disease in silkworm was recorded by Agostine Bassi way back in 1835. Experiments with mineral oils as plant protectants were also reported in the 19th century. During the early 20th century, an ever-growing number of studies and proposal for biopesticides were developed (Chen 2014).

The first widely used biopesticide included spores of the bacteria *Bacillus thuringiensis* (Bt) isolated from a diseased silkworm by Japanese biologist Shigetane Ishiwata in 1901 (Chen 2014, Glare *et al.*, 2000). Ten years later, Ernst Berliner in Thuringen, Germany rediscovered it in a diseased caterpillar of flour moth. The Bt pathogen was classified in 1911 as type species *Bacillus thuringiensis* and remains the most widely used biopesticide till date. In the early 1920s, the French began to use Bt as a biological insecticide and the first commercially available Bt product, Sporeine, appeared in 1938. In the US in the 1950 s, widespread use of biopesticides began to take hold. In the later half of the 20th century, research and development continued at a low level because of the widespread adoption of cheaper but more toxic synthetic chemical insecticides. During this time, new products were developed and applied; especially in niche markets where petroleum based chemicals were not registered, not effective, or not economical. For example, in 1956, the Pacific Yeast Product Company developed an industrial process known as submerged fermentation, which allowed production of Bt on a large scale (Glare *et al.*, 2000). In 1973, *Heliothis* NPV was granted exemption from tolerance and the first viral insecticide, Elcar

received a label in 1975. In 1977, *Bacillus thuringiensis* var. *israelensis* (toxic to flies) was discovered, and in 1983 the strain *tenebrion is* (toxic to beetles) was found. In 1979, the U.S. EPA registered the first insect pheromone for use in mass trapping of Japanese beetles. In the 1990s, researchers began testing kaolin clay as an insect repellent in organic fruit orchards. It was made commercially available, particularly for use in organic systems, in 1999 (Marrone *et al.*, 2002).

Biopesticide development for the control of plant diseases has undergone a similar transformation. During the early 20th century, studies of soil microbiology and ecology had led to the identification of many different microorganisms that act as antagonists or hyperparasites of pathogens and insect pests. A number of these were shown to be useful in field-scale inoculations, but few were developed commercially because of the rapid adoption of chemical pesticides during that time period (Chen 2014). Research into biological control of insect pests and pathogens slowed after the discovery of synthetic pesticide molecules during/after World War II. Renewed interest in biological pest management was stimulated following the demonstration by environmentalists and ecologists that broad and repeated application of these synthetic molecules could be ecologically harmful (Cook and Baker 1983). Commercial success stories from the 1980s and 1990s include products containing *Agrobacterium radiobacter* for the prevention of crown gall on woody crops and *Pseudomonas fluorescens* for the prevention of fire blight in orchards where the streptomycin had been overused and resistant pathogen populations were abundant. In the greenhouse and potting mix industry, products containing a variety of microbes that suppressed soilborne pathogens were introduced into the market.

The genus *Trichoderma* was discovered by Persoon in 1794 but captured the attention only after Weindling and his associates showed that one species of the genus can kill other fungi and control plant diseases (Weindling 1932 and 1934). However, the first field success of biological control (target *Sclerotium rolfsii*) using *Trichoderma* was not until the 1970s (Weindling 1934). Applied and fundamental research on these fungi has continued since in biotechnology and agriculture.

Present scenario and future projection

Presently, biopesticides cover only 2% of the plant protectants used globally; however its growth rate shows an increasing trend in past two decades. Agricultural biologicals have recorded double-digit sales growth and have accrued around US \$2.3 billion in annual sales over the past few years (Cuddeford and Kabaluk, 2010). Around two-thirds of US \$2.3 billion is contributed by microbial formulations alone (Cuddeford and Kabaluk 2010).

The global market of bioagents is expected to reach \$4 billion by 2024 from \$2 billion in 2016, growing at a CAGR of 8.8% from 2016 to 2024 (Fig. 1). Similarly, global investment in biopesticides was US\$1.3 billion in 2011 and is estimated to reach US \$ 3.2 billion by 2017, with at 15.8 % compound annual growth rate from 2012 to 2017 (www.markets and markets.com). These formulations include live microbial cells and microbial active ingredients for seed treatment and foliar applications (www.naasindia.org). There are about 1400 biopesticides currently sold globally, and is estimated that the annual growth rate of the biopesticide sector is greater than that of synthetic pesticides (16% versus 3%) (www.naasindia.org). The USA accounts for 40% of the global biopesticide use, followed by

Europe (20%) and Oceania (20%) (www.naasindia.org). However, the usage of bioagents is only about 20% of that of synthetic fertilizers (www.fao.org).

In India, biopesticide industry is projected to grow at a CAGR of 20.2 % since 2010 -2020. Scope of Current market for pesticides was US\$ 23.92 million in 2015 which represent only 4.2 % of the overall pesticide market. Currently, 34 microorganism have been included in the schedule of Gazette of India for registration as biopesticide with Central Insecticide Board, Faridabad, under section 9 (3B) and 9(3) of the insecticide act 1968 (Table 1) (Keswani *et al.*, 2015). Over 150 Bio pesticide producing companies, 15 types of bio pesticides out of 227 pesticides are registered. Highest demand for bio pesticides was observed from West India - Maharashtra followed by South India. Microbial pesticides sale are dominated by *Trichoderma viride*, *Pseudomonas fluorescens* and *Bacillus thuringiensis*, (Ken research Report 2015). Central insecticide Board and registration Committee, Government of India have registered more than 970 Bio pesticide product. More than 63 Indian Private Companies with Registered Products. Some Major Indian Companies for Bio pesticides: Pest Control (Pvt) Ltd; Multiplex Biotech Ltd., International Panacea, Biotech International Ltd; T. Stanes; etc.

The biopesticides market has been segmented in different ways. On the basis of type, the biopesticides market is led by the bioinsecticides segment, followed by the bioherbicides, biofungicides, and bionematicides segments and others (sulfur, oil, insect repellent, moth control, and other biochemicals) respectively. The bioinsecticides segment is projected to be the fastest-growing type in the biopesticides market, due to the high crop loss by pests and diseases (Fig. 2).

On the basis of crop type, classified as Grains & oilseeds, Fruits & vegetables, Others (turf, plantation, sugar crops, cotton, and ornamental crops). The market for fruit & vegetable crops accounted for the largest share and is also projected to be the fastest-growing. This is mainly due to a high demand for fruits & vegetables by the growing population across the world. Biopesticides market share from fruits & vegetables accounted for over 70% of the overall industry revenue (www.marketsandmarkets.com). As many fruits & vegetables are eaten without proper processing, consumers demand for better crop safety processing. Pesticide residue is generally a concern among consumers in these crops than in row crops that are not consumed in raw form. This practice leads to a high increase in pressure on grocery stores and good marketers to offer pesticide-free fruits & vegetables. Grains & oil seeds will observe gains over 6% up to 2024 (www.naasindia.org). Oats, vegetables, grains, and oilseeds are majorly contributing crops. The products prevent the generation of pathogens in the yield and enhance crop productivity. Other segment includes pulses, turfs, forage, and greenhouse crops.

The different modes of applications for biopesticides are foliar spray, soil treatment, seed treatment, and post-harvest. Foliar spray is highly used for applying biopesticides. To improve quality of crops and increase productivity of plants, foliar spray is effectively used to control pests on crops. The increases in acceptance of biological microbes and smart farming techniques have proven to be a major driving factor for the foliar application. These are marketed as dry and Liquid formulation (www.marketsandmarkets.com).

On the basis of Origin, it is classified as Microbial pesticides, Biochemical pesticides,

Beneficial insects, Plant-incorporated protectants and lastly, by geography the biopesticides market is segmented on the basis of region into North America, Europe, Asia-Pacific, and the Rest of the World (RoW). The U.S, Mexico and Canada are covered under North America wherein Europe covers France, Germany, Italy, Spain and others. Asia Pacific covers China, India, Japan and others and rest of the World (RoW) covers South America, Middle East and Africa. In 2015, North America accounted for the largest market share in the biopesticides market, followed by Europe and Asia-Pacific. U.S. and Canada constituted the largest country-level markets in the North American region in 2015 (Ken Research report, 2015). Increase in awareness about the benefits of biopesticides, among the cultivators and rise in population is leading to the growth of the market in this region. The biopesticides market in the Asia-Pacific region is projected to grow with investments from several multinational manufacturers. The market is projected to grow due to the increase in agricultural technologies and agricultural exports of key products. Moreover, extensive R&D initiatives have been undertaken for exploring the new varieties of biopesticides to be used on different pest management and soil fertility to increase the yield.

Research and development in biopesticide based pest management

Out of all the biopesticides used today, microbial biopesticides constitute the largest group of broad-spectrum biopesticides, which are pest specific (i.e., do not target non-pest species and are environmentally benign). Over 200 microbial biopesticides are available in 30 countries affiliated to the Organization for Economic Co-operation and Development (OECD) (Kabaluk and Gazdik 2007). There are 53 microbial biopesticides registered in the USA, 22 in Canada and 21 in the European Union (EU) (Kiewnick, 2007

and PMRA. In) although reports of the products registered for use in Asia are variable (Thakore, 2006). Overall, microbial biopesticide registrations are increasing globally, the expansion of various technologies has increased the scope for more products and the change in the trend to develop microbial products is definitely on the rise (Bailey *et al.*, 2010 and Kristiofferesen *et al.*, 2008).

Bacterial biopesticides

The bacteria that are used as biopesticides can be divided into four categories: crystalliferous spore formers (such as *Bacillus thuringiensis*); obligate pathogens (such as *Bacillus popilliae*); potential pathogens (such as *Serratia marcescens*); and facultative pathogens (such as *Pseudomonas aeruginosa*). Out of these, the spore formers have been most widely adopted for commercial use because of their safety and effectiveness. The most commonly used bacteria are *B. thuringiensis* and *Bacillus sphaericus*. *B. thuringiensis* is a specific, safe and effective tool for insect control (Roy *et al.*, 2007).

It is primarily a pathogen of lepidopterous pests like American bollworm in cotton and stem borers in rice. When ingested by pest larvae, Bt releases toxins which damage the mid gut of the pest, eventually killing it. Main sources for the production of BT preparations are the strains of the subspecies *kurstaki*, *galeriae* and *dendrolimus*. Other species of bacteria have little impact on pest management though some commercial products based on *Agrobacterium radiobacter*, *B. popilliae*, *B. subtilis*, *Pseudomonas cepacia*, *Pseudomonas chlororaphis*, *Pseudomonas fluorescens*, *Pseudomonas solanacearum* and *Pseudomonas syringae* are available (Table 2).

Viral biopesticides

Over 700 insect-infecting viruses have been isolated, mostly from Lepidoptera (560) followed by Hymenoptera (100), Coleoptera, Diptera and Orthoptera (40) (Khachatourians 2009). About a dozen of these viruses have been commercialized for use as biopesticides (Table 2). The viruses used for insect control are the DNA-containing baculoviruses (BVs), Nucleopolyhedrosis viruses (NPVs), granuloviruses (GVs), acoviruses, iridoviruses, parvoviruses, polydnviruses, and poxviruses and the RNA-containing reoviruses, cytoplasmic polyhedrosis viruses, nodaviruses, picorna-like viruses and tetraviruses. However, the main categories used in pest management have been NPVs and GV. These viruses are widely used for control of vegetable and field crop pests globally, and are effective against plant-chewing insects. Their use has had a substantial impact in forest habitats against gypsy moths, pine sawflies, Douglas fir tussock moths and pine caterpillars.

Codling moth is controlled by *Cydia pomonella* GV on fruit trees (Lacey *et al.*, 2008) and potato tuberworm by *Phthorimaea operculella* GV in stored tubers (Arthurs *et al.*, 2008). Virus-based products are also available for cabbage moths, corn earworms, cotton leafworms and bollworms, beet armyworms, celery loopers and tobacco budworms (Table 2). Baculoviruses are target specific viruses which can infect and destroy a number of important plant pests. They are particularly effective against the lepidopterous pests of cotton, rice and vegetables. Their large-scale production poses certain difficulties, so their use has been limited to small areas. They are not available commercially in India, but are being produced on a small scale by various IPM centres and state agricultural departments.

Fungal biopesticides

Some of the most widely used species include *Trichoderma harzianum*, *Trichoderma viridae*, *Streptomyces griseoviridis*, *Verticillium chlamydosporium*, *Beauveria bassiana*, *Metarhizium anisopilae*, *Nomuraea rileyi*, *Paecilomyces farinosus* and *Verticillium lecanii* etc. Many of them have been commercialized globally (Table 2). *Trichoderma* is a fungicide effective against soil borne diseases such as root rot. It is particularly relevant for dryland crops such as groundnut, black gram, green gram and chickpea, which are susceptible to these diseases. Preparation of *Trichoderma* biopesticide is cheap and requires only basic knowledge of microbiology. This bio-fungicide is recommended as seed treatment, soil application, soil drenching, root dip technique etc for the control of seed and soil borne diseases. Many *Trichoderma* strains, mainly *T. harzianum*, *T. viride* and *T. virens* (formerly *Gliocladium virens*), have been identified as having potential applications in biological control and a partial list of genera of plant pathogenic fungi affected by *Trichoderma* includes: *Armillaria*, *Botrytis*, *Chondrostereum*, *Colletotrichum*, *Dematophora*, *Diaporthe*, *Endothia*, *Fulvia*, *Fusarium*, *Fusicladium*, *Helminthosporium*, *Macrophomina*, *Monilia*, *Nectria*, *Phoma*, *Phytophthora*, *Plasmopara*, *Pseudoperonospora*, *Pythium*, *Rhizoctonia*, *Rhizopus*, *Sclerotinia*, *Sclerotium*, *Venturia*, *Verticillium*, and wood rot fungi (Singh, 2014). Recent studies also indicate potential use of *Trichoderma* strains in abiotic stress management i.e., drought and salt stress (Shukla *et al.*, 2012 and Rawat *et al.*, 2011)

Nematode biopesticides

Another group of microorganisms that can control pests is the entomopathogenic nematodes, which control weevils, gnats,

white grubs and various species of the Sesiidae family (Klein, 1990; Shapiro-Ilan *et al.*, 2002; Grewal, 1990). These fascinating organisms suppress insects in cryptic habitats (such as soil-borne pests and stem borers). Commonly used nematodes in pest management belong to the genera *Steinernema* and *Heterorhabditis*, which attack the hosts as infective juveniles (IJs) (Kaya and Gaugler, 1993; Koppenhofer and Kaya, 2002).

Protozoan biopesticides

Although they infect a wide range of pests naturally and induce chronic and debilitating effects that reduce the target pest populations, the use of protozoan pathogens as biopesticide agents has not been very successful. Protozoa are taxonomically subdivided into several phyla, some of which contain entomogenous species. Microsporean protozoans have been investigated extensively as possible components of integrated pest management programmes.

Opportunities in India

Harmful impact of chemicals such as higher pesticides residues in food crops, specifically on grains and increasing pest resistance has brought into focus the use of safer and effective alternative such as bioagents/biopesticides. Moreover, the area under organic crop cultivation is on the rise because of the growing demand of organic food, a result of increasing health consciousness among the people. This indicates that there is huge scope for growth of the biopesticide sector. Analysts believe that there would be a greater development in the biopesticides sector (Desai 1997). Due to its rich biodiversity India offers plenty of scope in terms of sources for natural biological control organisms as well as natural plant based pesticides. The rich

traditional knowledge base available with the highly diverse indigenous communities in India may provide valuable clues for developing newer and effective biopesticide. The National Farmer Policy 2007 has strongly recommended the promotion of biopesticides for increasing agricultural production, sustaining the health of farmers and environment. It also includes the clause that biopesticides would be treated *at par* with chemical pesticides in terms of support and promotion. Increased adoption further depends on-

1. Concrete evidences of efficacy of biopesticides in controlling crop damage and the resultant increase in crop yield
2. Availability of high quality products at affordable prices
3. Strengthening of supply chain management in order to increase the usage of biopesticides. In this regard, an efficient delivery system from the place of production (factory) to place of utilization (farm) of biopesticides is quite essential.

Future prospects:

The biopesticide market will continue to grow in future due to increased pest resistance problem and high demand of safe and quality food products. However, there are many challenges that will need to be overcome.

Biopesticides clearly draw attention as safer alternative to manage pest and diseases while posing less risk to human being and the environment. In the US, biopesticides are monitored by Environmental Protection Agency which supports their registration, sale and distribution under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), as well as ensures a “reasonable certainty of no harm” under the Federal Food, Drug, and

Cosmetic Act (FFDCA) to provide pesticide residue-free food and feed (Leahy *et al.*, 2014). Most of the times, it is the farmers who are affected by the problems of pesticide resistance and withdrawal of plant protection products, and yet they are ‘policy takers’

rather than ‘policy makers’. Hence, a public-private sector approach to the development, manufacturing and sale of environment friendly alternatives to chemical pesticides for developing countries like India is the need of the day.

Table.1 Microbial pesticides included in the schedule to the Insecticide Act, 1968

Bacterial	Fungal	Viral
<i>Burkholderia cepacia</i>	<i>Verticillium chlamyosporium</i>	<i>Grannulosis viruses</i>
<i>Agrobacterium radiobacter</i> strain 84	<i>Streptomyces griseoviridis</i>	<i>Nuclear Polyhedrosis Viruses (NPV)</i>
<i>Agrobacterium tumefaciens</i>		
<i>Erwinia amylovora</i> (hairpin protein)	<i>Streptomyces lydicus</i>	
<i>Alcaligenes spp</i>	<i>Candida oleophila</i>	
<i>Photobacterium luminescens</i> akhurstii strain K-1	<i>Fusarium oxysporum</i> (non pathogenic)	
<i>Photobacterium luminescens</i>	<i>Penicillium islanidicum</i>	
<i>Serratia marcescens</i> GPS 5	<i>Pythium oligandrum</i>	
<i>Bacillus subtilis</i>	VAM (Fungus)	
<i>Pseudomonas fluorescence</i>	<i>Aspergillus niger</i> – strain AN27	
	<i>Beauveria bassiana</i>	
	<i>Metarrhizium anisopliae</i>	
	<i>Verticillium lecanii</i>	
	<i>Trichoderma harzianum</i>	
	<i>Nomurea rileyi</i>	
	<i>Hirsutella species</i>	
	<i>Ampelomyces quisqualis</i>	
	<i>Phlebia gigantean</i>	
	<i>Coniocytrium minitans</i>	
	<i>Myrothecium verrucaria</i>	
	<i>Paecilomyces lilacinus</i>	
	<i>Chaetomium globosum</i>	
	<i>Piriformospora indica</i>	

Table.2 Commercial microbial biopesticides developed for plant disease management

Mirco-organism	Target pest	Action	Brand name	Producer
<u>Bacteria</u>				
<i>A. radiobacter</i>	Crown galls	Antagonist	Galltrol-A Dygal Norbac 84-C* Nogall	AgBioChem Agbioresearch Ltd New BioProducts Becher Underwood
<i>B. pumilus</i>	Effective against rust, downy and powdery mildews	Fungicide	Ballad Sonata AS YeildShield	Agraquest Inc. Gustafson LLC
<i>B. subtilis</i>	Effective against root rot caused by Rhizoctonia, Fusarium, Alternaria, Aspergillus and Pythium Also effective against some foliar diseases	Fungicide and antagonist	Serenade Epic Kodiak MBI 600 Companion** Cillus Green-all G HiStich N/T** Subtiex	AgraQuest, Inc. Gustafson, Inc. Growth Products Green Biotech, Korea Becker Underwood
<i>B. subtilis</i> FZB24	Effective against Rhizoctonia, Fusarium, Alternaria, Verticillium and Streptomyces on vegetables and ornamental plants	Fungicide	Rhizo-Plus Rhizo-Plus Konz	FZB Biotechnik, GmbH
<i>Erwinia amylovora</i> (Hrpn harpin protein)	Multi-spectrum	Insecticide, fungicide and nematocide	Messenger	Eden Biosciences
<i>P. cepacia</i>	Effective against soil pathogenic fungi	Toxic	Intercept	Soil Tech
<i>P. chlororaphis</i>	Effective against fungal pathogens of barley and oats	Seed treatment control	Cedomon	BioAgri AB

<i>P. flourescens</i>	Effective against <i>P. tolasii</i> on mushrooms and <i>Erwinia</i> on fruit crops	Antibacterial	Conquer Blight Ban A506	Mauri Foods NuFarm Inc
<i>P. solanacearum</i>	Bacterial control in vegetables	Antibacterial	PSSOL	NPP, Korea
<i>P. syringae</i>	Effective against post-harvest pathogens on apples, pears and citrus	Antagonist	Bio-Save	Het Harvest Solutions
<i>Pseudomonas</i> + <i>Azospirillum</i>	Effective against brown patch and dollar spot soil pathogens	Antagonist	BioJet	Eco-Soil
<u>Fungi</u>				
<i>Ampelomyces quisqualis</i>	Powdery mildew control and damping off disease control	Hyperparasitic	Q-Fect Green-all	Green Biotech, Korea
<i>Burkholderia cepacia</i>	Effective against soil fungal pathogens	Controls fungi via seed treatment	Deny	Stine Microbial Products
<i>Candida oleophila</i>	Effective against postharvest pathogens like <i>Botrytis</i> and <i>Penicillium</i>	Colonization of diseased tissues	Aspire	Ecogen
<i>Coniothyrium minitans</i>	Effective against <i>Sclerotinia</i> species on canola, sunflower, peanut, soyabean and vegetables	Mode-of-action not clear	Contans WG KONI	Prophyta Biologischer GmbH BIOVED Ltd.
<i>Fusarium oxysporum</i> (non-pathogenic)	Effective against pathogenic <i>Fusarium</i> on basil, carnation, cyclamen, tomato	Seed treatment and soil incorporation	Biofox C Fusaclean	SIAPA NPP, France
<i>Gliocladium catenulatum</i> <i>Gliocladium</i> spp.	Effective against <i>Pythium</i> , <i>Rhizoctonia</i> , <i>Botrytis</i> and <i>Didymella</i> species on greenhouse	Mode-of-action not clear	Primastop GlioMix Prestop	Verdera Oy, Finland Fargo, UK

	crops			
<i>Gliocladium virens</i>	Effective against soil pathogens causing damping off and root rot	Antagonist	Soil Guard 12G	Certis LLC
<i>Phelbia gigantea</i>	Effective against pine and spruce rust	Biofungicide	Rotstop	Kemira
<i>Phytophthora palmivora</i> <i>Pythium oligandrum</i>	Vine strangler Management of fungal pathogens in various crops	Infects via roots Seed treatment or soil incorporation	DeVine Polyversum	Abbott Biopreparaty Ltd., Czech
<i>Streptomyces griseoviridis</i>	Effective against wilt, seed rot and stem rot	Antagonist	Mycostop Mycostop Mix	Verdera Oy and Rincon Vitova
<i>Streptomyces lydicus</i>	Effective against soil borne diseases of turf, nursery crops	Fungicide	Actinovate SP	Natural Industries Inc
<i>Talaromyces flavus V117b</i>	Effective against fungal pathogens of tomato, cucumber, strawberry and rape oilseeds	Antagonist	Protus WG	Peophyta Biologischer Pflanzenschutz
<i>Trichoderma harzianum</i>	Effective against variety of soil pathogens and wound pathogens	Mycoparasitic, Antagonistic	RootShield Bio Trek 22g Supresivit	Bio Works Inc Wilbur-Ellis Borregaard, Denmark
<i>T. harzianum</i> + <i>T. viride</i>	Effective against Armillaria and Botryoshaeria and others	Mycoparasitic	Trichopel Trichojet Trichodowels Trichoseal	Agrimm Tech
<i>Trichoderma sp.</i>	Supresses root pathogens	Mycoparasitic	Trichodry Trichoflow Trichogrow Trichopel Vinevax	Agrimm Technologies Ltd. New Zealand
<i>Trichoderma viride</i>	Effective against rot diseases	Mycoparasitic	Ecosom TV Tricon	Agri Life GreenMax Agro Tech Ecosense labs

(*products discontinued, **products having EPA experiemental use permit)

Fig.1 Biopesticides market size and forecast (2015-2024) in US\$ Billion

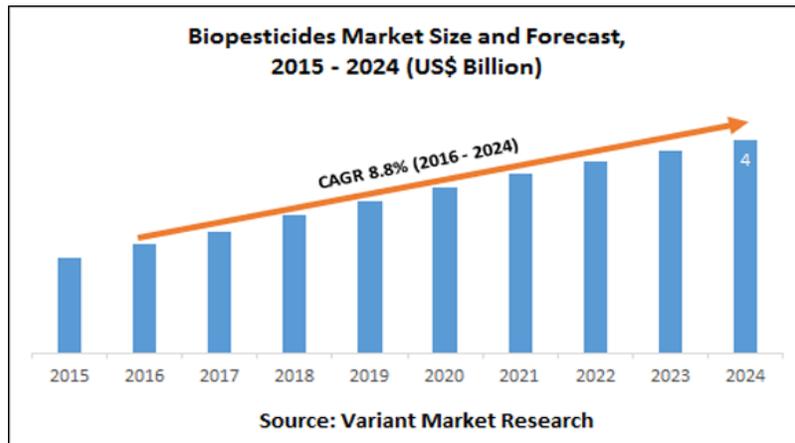
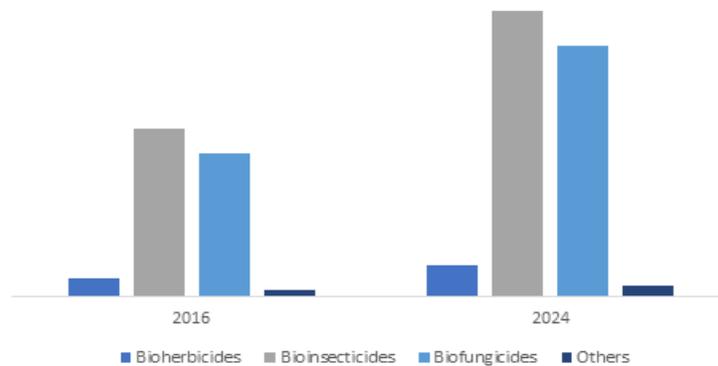


Fig.2 Growth of biopesticides on the basis of type



In fact, there is a need for well-defined selection criteria i.e. toxicity, production efficiency and safety of the product. Besides, most jurisdictions recognize that biopesticides are fundamentally different to synthetic pesticides. Concerted efforts to modify regulations will be crucial to boost development of new biopesticides. More research is required towards integrating biological agents into production system, improving capability of developing countries to manufacturing and commercialization of biopesticides. At the same time, it is also required to encourage public funded programmes, commercial investors and pesticide companies to take up biopesticide

enterprises. Strict regulatory mechanisms to maintain the quality parameter and availability of the biopesticides at affordable cost in the developing countries must be followed. Thus, various aspects of biopesticides covering the current status, constraints, prospects and regulatory network towards their successful utilization for the benefit of people and environment need to be examined regularly.

Progress has clearly been made, with many new biopesticides on the market and technological developments continuing to overcome impediments. However, in our opinion, they have not yet reached their

potential, even though all predictions suggest biopesticides will outperform other pest control options in terms of market share increases in the near future. We see a bright future for biopesticides, if the research and industry groups can think bigger and act united, better communicate the positive messages about biopesticides, and demonstrate their ability to control pests effectively and economically.

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