2 Biopesticides: Where We Stand?

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Abstract

Chemical pesticides are well known for their effective role in disease management because not only they act on a broad host range but production technology is also less expensive. However, the devastating part is their huge negative impact on the environment including the living beings of the planet. In spite of this, in the absence of suitable alternative, the use of synthetic pesticides has dominated around the globe. By the advent of greener approach of developing and using biopesticides, the situation is gradually changing but in fact can move far more swiftly in this direction which will be sustainable and eco-friendly. Although biopesticides are slowly replacing the chemical pesticides, a complete global look at the scenario indicates that the former and particularly the industries based on them are still in an insecure position in comparison to the chemicals which rule the agriculture. We can say that the biopesticides, although show a great promise, have not come up to the desired level so as to displace the dominance of chemicals. In this chapter, the global scenario of biopesticides is discussed emphasizing upon the current demand, use, constraints, and remedies.

Introduction

Two-thirds of today's world population depends upon agriculture for livelihood, but nowadays, growth and production of agricultural crops are getting hampered day by day (Elumalai and Rengasamy 2012). When farmers see their agricultural crops declining in yield and production, they often expect a dramatic, magical treatment to make them lush, green, and healthy again, so that the productivity increases. As a result, they start using chemical pesticides, disregarding their future effects. The extensive use of these synthetic organic chemicals in the past decades has led to a number of long-term environmental problems (Arora et al. 2012). Keeping all these

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facts in mind, a very big challenge in the new millennium is to produce more and more food from shrinking per capita arable land, keeping the environment safe and innocuous.

As agricultural production intensified over the past few decades, producers became more and more dependent on agrochemicals. The conventional chemical pesticides have although enhanced the food production, but have also adversely affected the environment and nontarget organisms. Chemical fertilizers and pesticides are continuously accumulating in the environment, harming the ecosystem, causing pollution, and inflicting diseases at alarming levels (Gerhardson 2002; Arora et al. 2010). The heavy use of pesticides has already caused grave damage to health, ecosystems, and groundwater. Many of the pesticides currently being used have the tendency to survive in plants for a long time. They also enter the food chain and are found in meat and dairy products and remain as residue in the soil and ecosystem for long durations.

Therefore, it is very urgent to identify alternatives to chemical pesticides for plant protection without sacrificing the productivity and profitability of agriculture. Due to the side effects of chemical pesticides, sustainable crop production through eco-friendly management is essentially required in the present scenario.

Biopesticides offer powerful tools to create a new generation of sustainable agriculture products. They are the most likely alternatives to some of the most problematic chemical pesticides currently in use. Biopesticides offer solutions to concerns such as pest resistance, traditional chemical pesticides, and public concern about side effects of pesticides on the surrounding environment and ultimately on human health. The overriding challenge for the biopesticide industry is to live up to the promises and expectations of the end users or the market and public as whole. There are unanswered questions and unexamined assumptions about these biological and eco-friendly alternatives. Challenges to biopesticides stem from questions about their efficacy and safety, public and grower confusion about the spectrum of biopesticide products in the market, and current market conditions that paradoxically both hinder and favor the field's growth.

The aim of the review is to highlight the present global scenario of biopesticides, including its market, availability, and usefulness. Besides this, the compilation also addresses the possible constraints and dilemmas associated with biopesticides throughout the globe and the direction to what should be explored in the future to uplift the stature. Biopesticides offer an environmentally sustainable approach to increase crop production and health, contributing substantially in making the twenty-first century the age of biotechnology hence every effort should be made to enhance their use and popularity.

Shift of Wheel from Pesticides to Biopesticides

It is well known that there have been some discoveries in the past which not only have changed the life of man but also had major influence on the globe, and a very well-known chemical pesticide para-dichlorodiphenyltrichloroethane (DDT) was one of them (West and Campbell 1946). After World War II, its discovery was considered as important as that of penicillin (Felix 1958). In one way when penicillin was saving the life of millions from life-threatening bacterial infections, DDT was protecting crops from a variety of pests. Although for a few years the glory of DDT was extolled by everyone, but soon the whole picture started to change. For the first time, Rachel Carson, a marine biologist and conservationist, stated in her book *Silent Spring* that we are paying much more than what we are getting to get rid of mosquitoes (Carson 1962). Finally in the USA, DDT was banned in 1972 (Griswold 2012). There are myriads of incidences dealing with DDT poisoning that are already known and some are needed to be further explored (Hill and Robinson 1945; Dresdend 1948; Keane 1972; Tschirley 1973; Longnecker et al. 1997; Conis et al. 2010; Qiu 2013). DDT was not the only culprit; other categories of synthetic pesticides such as organophosphates (OP), carbamates, and pyrethroids were also launched, and by 1980, their impact on pest control and environment was also well recognized (Aktar et al. 2009).

OP are advanced over organochlorines being nonpersistent in environment and do not cause bioaccumulation in the food chain; however, they are much more acutely toxic to humans and other mammals than organochlorines, and their exposure by inhalation, swallowing, or absorption through the skin can lead to immediate health problems (Baird and Cann 2008). Mostly people residing in agricultural areas, farmworkers, and small children are more frequently exposed to hazards of organophosphates (Landrigan et al. 1999; Eskenazi et al. 1999; Fenske et al. 2000; McCauley et al. 2001; Quandt et al. 2004; Eskenazi et al. 2008). Acute toxicity of organophosphates and carbamates is a severe problem in developing countries, and ignorance about their hazards and the lack of information have led to many deaths among agricultural workers (Konradsen et al. 2003). A high proportion of pesticide poisonings and deaths occur in developing countries, and the main victims are farming workers especially those having insufficient knowledge of pesticide hazards (Pimentel and Greiner 1996). Intensive use of synthetic pesticides created more harsh ecological conditions that resulted in reduced soil fauna and habitat loss of micro- and macroflora (Edwards and Thompson 1973; Tripathi and Sharma 2005; Frampton et al. 2006; Bezchlebová et al. 2007). Recent studies showed that the increased use of pesticides is responsible for the vanishing population of bees and several other useful insects involved in pollination of flowers of agriculturally important crops (Gill et al. 2012). In a similar study, pesticide exposure raised question on global decline of frog population (Brühl et al. 2013). Even several species of birds have become extinct or are on the verge of it because of the pesticides. It can also be concluded that the negative impact of pesticides is much more than what is visible by the aid of the present technology.

By 2001, over 100 nations in Stockholm Convention agreed to sign an international treaty to phase out completely persistent organic pollutants ("POPs"), including DDT (Downie 2003). Albeit the synthetic pesticides have showed devastating effect on the ecosystems, in the absence of an alternative, it was impossible to diminish their utility and effects (Wu and Chen 2004; Aktar et al. 2009). Meanwhile, a phrase by Roger Ascham "Necessitie, the inuentour of all goodnesse" proved to be true for some workers in the field of biological control. Pioneer workers such as A. Bassi in Italy, V. Auduoin in France, J. Le Conte in the USA, and E. Metchnikoff in Russia proposed that antagonistic microbes might be useful in controlling crop pests and may be alternatives to synthetic pesticides (Le Conte 1874; Steinhaus 1949, 1957, 1975; McCoy et al. 1988). Later, these pioneer discoveries and further researches proved to be milestones in development of microbe-based pesticides (Schönbeck and Dehne 1986; Sundheim and Tronsmo 1988).

In the eighteenth century and even in the beginning of the nineteenth century, the focus of biological control was to use animals such as birds and entomophagous insects; microbes were not even properly known at that time. The discovery of *Bacillus thuringiensis* (Bt) showed a wider aspect of microbe-based biological control (Aronson et al. 1986; Martin and Traverse 1989; Siegel and Shadduck 1990; Marrone 1994; Joung and Coˆte' 2000). Microbial pest control was a very new concept, and its selective action on pest attracted the concentration of researchers and industrialists equally, and soon the first commercial Bt product, Thuricide, was registered in the USA in 1961 (USEPA 1998). Since then, different subspecies, varieties, and strains of Bt have been identified that are effective against a variety of insects (Gonzales et al. 1982; Carlton 1988). In a span of a very few years, Bt has covered up to 90 % of the whole biopesticide market (Chapple et al. 2000; Chattopadhyay et al. 2004; Romeis et al. 2006), and several Bt strains are now registered as biopesticides throughout the world (Glare and O'Callaghan 2000). In 1965, the first fungal product "Boverin" was developed in the former Union of Soviet Socialist Republics (USSR). In Boverin, *Beauveria bassiana* was used to control the Colorado potato beetle and the codling moth (De Faria and Wright 2007). In

1973, *Heliothis* nuclear polyhedrosis virus (NPV) was first declared as a viral biopesticide (Szewczyk et al. 2011). In the last few years, although several new biopesticides have been registered and served as better alternatives to synthetic pesticides, they still lack far behind the chemicals and the desired levels (Clemson 2007). Biopesticides have emerged as alternatives to chemical pesticides, and we also know their importance and benefits, but in reality to date, the goals have not been attained and chemicals still rule throughout the globe.

Concept of Biopesticides

In very general terms, according to the US Environmental Protection Agency (USEPA), biopesticides are pesticides derived from natural materials such as animals, plants, bacteria, and minerals. Biopesticides also include living organisms that destroy agricultural pests. The EPA separates biopesticides into three major classes based on the type of active ingredient used, namely, biochemical, plant-incorporated protectants, and microbial pesticides (USEPA 2008). Biochemical pesticides are chemicals either extracted from natural sources or synthesized to have the same structure and function as the naturally occurring chemicals. Biochemical pesticides are distinguished from conventional pesticides both by their structure (source) and mode of action (mechanism by which they kill or control pests) (O'Brien et al. 2009). At a global level, there is an inconsistency in understanding the term biopesticide as aforementioned operative definition of the term biopesticide given by USEPA is not followed in the entire world and that is why International Biocontrol Manufacturer's Association (IBMA) and the International Organization for Biological Control (IOBC 2008) promote to use the term biocontrol agents (BCAs) instead of biopesticide (Guillon 2003). IBMA classifies biocontrol agents into four groups: (1) macrobials, (2) microbials, (3) natural products, and (4) semiochemicals (insect behavior-modifying agents). Among all the biocontrol agents, the most important products are microbials (41 %), followed by macrobials (33 %), and, finally, other natural products (26 %) (Guillon 2003). This review focuses on microbe-based biopesticides.

Microbial Pesticides

Microbial pesticides are also known as BCAs. They offer the advantages of higher selectivity and lower or no toxicity in comparison to conventional chemical pesticides (MacGregor 2006). The active ingredient of a microbial pesticide is typically the microorganism. Microbial ingredients can be either the spores or the organisms themselves. The most commonly used microbial biopesticides are living organisms, which are pathogenic for the pest of interest. These include biofungicides (*Trichoderma*, *Pseudomonas*, *Bacillus*), bioherbicides (*Phytophthora*), and bioinsecticides (*Bt*) (Gupta and Dikshit 2010). Microbial pesticides come from naturally occurring or genetically altered bacteria, fungi, algae, viruses, or protozoans. They suppress pests either by producing toxic metabolites specific to the pest, causing disease, preventing establishment of other microorganisms through competition, or various other modes of action (Clemson 2007). Of the total biopesticide market for all crop types, bacterial biopesticides claim about 74 %; fungal biopesticides, about 10 %; viral biopesticides, 5 %; predator biopesticides, 8 %; and "other" biopesticides, 3 % (Thakore 2006). By 2008, there were approximately 73 microbial active ingredients that were registered by the USEPA. The registered microbial biopesticides included 35 bacterial products, 15 fungi, 6 nonviable (genetically engineered) microbial pesticides, 8 plant-incorporated protectants, 1 protozoan, 1 yeast, and 6 viruses (Steinwand 2008). Microbial biopesticides may be delivered to crops in many forms including live organisms, dead organisms, and spores, and the next subsection presents various forms of microbe-based pesticides that are being used presently.

Bacterial Biopesticides

Bacterial biopesticides are the most common form of microbial pesticides that function in multiple ways. Generally, they are used as insecticides, although they can be used to control the growth of plant pathogenic bacteria and fungi. As an insecticide, they are generally specific to individual species of moths and butterflies or species of beetles, flies, and mosquitoes. To be effective, they must come into contact with the target pest and may be required to be ingested. In insects, bacteria disrupt the digestive system by producing endotoxins that are often specific to the particular insect pest. When used to control pathogenic bacteria or fungus, the bacterial biopesticide colonizes on the plant and crowds out the pathogenic species (O'Brien et al. 2009).

The members of the genus *Bacillus* are often considered as microbial factories for the production of vast array of biologically active molecules, some of which are potentially inhibitory for fungal growth (Schallmey et al. 2004). The most widely used microbial pesticides are subspecies and strains of *B. thuringiensis* (Bt), accounting for approximately 90 % of the biopesticide market in the USA (Chattopadhyay et al. 2004). Since its discovery in 1901, Bt has been widely used to control insect pests important in agriculture, forestry, and medicine (Mazid and Kalita 2011). Its principal characteristic is the synthesis, during sporulation, of crystalline inclusions containing proteins known as δ endotoxins or Cry proteins, which have insecticidal properties. To date, over one hundred *B. thuringiensis*-based bioinsecticides, biopesticides, and biofungicides have been developed. Microbial pesticides containing *B. thuringiensis* var. *kurstaki* kill the caterpillar stage of a wide array of butterflies and moths. In addition, the genes that code for the insecticidal crystal proteins have been successfully transferred into different crop plants including cotton, tomato, brinjal, etc. that lead to significant economic benefits. Due to their high specificity and safety in the environment, *B. thuringiensis* and Cry proteins are efficient, safe, and sustainable alternatives to chemical pesticides for the control of insect pests (Roy et al. 2007; Kumar 2012).

Plant pathogenic fungi and oomycetes are major threats for crop and plant production. Therefore, the control of fungal diseases by *Bacillus*-based biopesticides represents an interesting opportunity for agricultural biotechnology. Indeed, several commercial products based on various *Bacillus* species such as *B. amyloliquefaciens*, *B. licheniformis*, *B. pumilus*, and *B. subtilis* have been marketed as biofungicides (Fravel 2005). These *Bacillus*-based products have been developed especially for the control of fungal diseases. A high number of reports have described the beneficial effects of several *Bacillus* species against diseases elicited by oomycetes and fungal pathogens. Some examples are the suppression of root diseases (such as avocado root rot, tomato damping off, and wheat take-all), foliar diseases (such as cucurbit and strawberry powdery mildews), and postharvest diseases (such as green, gray, and blue molds) (Cazorla et al. 2007; Pertot et al. 2008; Arrebola et al. 2010). Certain strains of *B. subtilis* are being used against a range of plant pathogens that cause damping off and soft rots (Kloepper et al. 2004; Haas and Defago 2005; Berg 2009). Apart from this *B. pumilus* QST 2808, *B. subtilis* QST GB03 are used for designing biopesticides, namely, Ballad®Plus and Kodiak®, for commercial purposes in the USA (Stewart et al. 2011).

Due to their catabolic versatility and excellent root-colonizing capability, pseudomonads are also being investigated extensively for the use in biocontrol of pathogens in agriculture (Ganeshan and Kumar 2006). They are known to enhance plant growth and yield, reduce severity of many diseases, and are considered to be among the most prolific PGPRs (Hoffland et al.1996; Wei et al.1996). Several species of *Pseudomonas* are being used for designing biopesticides that include *P. fluorescence*, *P. aeruginosa*, *P. syringae*, etc. Certain strains of *Pseudomonas aureofaciens* are being used against a range of plant pathogens including damping off and soft rots (Kloepper et al. 2004; Haas and Defago

2005; Berg 2009). The cell suspensions of pseudomonads are immobilized on certain carriers and are prepared as formulations for easy application, storage, commercialization, and field use. In India, *P. fluorescens* biopesticide is effectively being used against late blight of potato; it is available commercially under diverse brand names such as Krishi bio rahat, Krishi bio nidan, Mona, etc. Virulent cells of bacterial antagonist *P. fluorescens* are taken to prepare a biopesticide formulation that is effective against phytopathogen *Ralstonia solanacearum* (Bora and Deka 2007; Chakravarty and Kalita 2011).

P. syringae strains ESC-10 and ESC-11 were initially registered (licensed for sale and distribution) in 1995; at the end of April 2000, there were three end products containing ESC-10 and 2 end products containing ESC-11 in the USA (Bull et al. 1997). An attractive role of fluorescent pseudomonads in biological control of fungal plant pathogens has been illustrated against *Aspergillus*, *Alternaria*, *Fusarium*, *Macrophomina*, *Pythium*, *Sclerotinia*, and *Rhizoctonia* (Dunne et al. 1998; Gupta et al. 2001). Several different commercially available biopesticides in the USA that are developed from *Pseudomonas* and effective against fungal phytopathogens are Spot-Less, At-Eze, Bio-Save 10LP, and Bio-Save 11LP (Vargas 1999; Nakkeeran et al. 2005; Khalil et al. 2013). Bioformulation, biopesticides, and bioinoculants developed from fluorescent pseudomonads can serve multifaceted functions of plant growth promotion, bioremediation, and disease management (Arora et al. 2008, 2013; Khare and Arora 2011; Tewari and Arora 2013).

Certain other bacterial strains like that of *Agrobacterium radiobacter* are also used to control pests such as *Agrobacterium tumefaciens*. Other PGPRs like *Pantoea agglomerans* strain E325, *Streptomyces lydicus* WYEC 108, and *Coniothyrium minitans* strain CON/M/91-08 are also used nowadays for designing new biopesticides such as Bloomtime Biological™[3], Actinovate®SP, and Contans®WG (in the USA) that are proving to be boon in the field conditions (Chunxue et al. 2010).

Fungal Biopesticides

The fungal pathogens play a major role in the development of diseases on many important field and horticultural crops, resulting in severe plant yield losses (Khandelwal et al. 2012). Intensified use of fungicides has resulted in accumulation of toxic compounds potentially hazardous to human and environment and also in the buildup of resistance in the pathogens. Fungal biopesticides can be used to control insects and plant diseases including other fungi, bacteria, nematodes, and weeds. The mode of action is varied and depends on both the pesticidal fungus and the target pest. One advantage of fungal biopesticides in comparison with many of the bacterial and all of the viral biopesticides is that they do not need to be eaten to be effective. However, they are living organisms that often require a narrow range of conditions including moist soil and cool temperatures to proliferate. Biocontrol agents like *Trichoderma* are acclaimed as effective, eco-friendly, and cheap, nullifying the ill effects of chemicals. Therefore, of late, these biocontrol agents are identified to act against an array of important soil-borne plant pathogens causing serious diseases of crops (Bailey and Gilligan 2004).

Fungal biopesticides used against plant pathogens include *T. harzianum*, which is an antagonist of *Rhizoctonia*, *Pythium*, *Fusarium*, and other soil-borne pathogens (Harman 2005). *Trichoderma* is a fungal antagonist that grows into the main tissue of a disease-causing fungus and secretes enzymes that degrade the cell walls of the other fungus and then consumes the contents of the cells of the target fungus and multiplies its own spores. *Trichoderma* is one of the common fungal biocontrol agents being used worldwide for suitable management of various foliar- and soil-borne plant pathogens like *Ceratobasidium*, *Fusarium*, *Rhizoctonia*, *Macrophomina*, *Sclerotium*, *Pythium*, and *Phytophthora* spp. (Dominguesa et al. 2000; Anand and Reddy 2009). *Trichoderma viride* has proved to be very promising against soil-borne plant parasitic fungi (Khandelwal et al. 2012). A specific strain *Muscodor albus* QST 20799 is a naturally occurring fungus originally isolated from the bark of a cinnamon tree in Honduras. When hydrated, this *M. albus* strain is reported to produce a number of volatiles, mainly alcohols, acids, and esters, which inhibit and kill certain bacteria and other organisms that cause soil-borne and postharvest diseases. Products containing QST 20799 can be used in fields, greenhouses, and warehouses (USEPA 2008).

B. bassiana (Balsamo) Vuillemin and *Metarhizium anisopliae* (Metchnikoff) Sorokin are naturally occurring entomopathogenic fungi that infect sucking pests including *Nezara viridula* (L) (green vegetable bug) and *Creontiades* sp. (green and brown mirids) (Sosa-Goméz and Moscardi 1998). Fungi have the unique ability to attack insects by penetrating through the cuticle making them ideal for the control of sucking pests. *B. bassiana* is currently registered in the USA as Mycotrol ES ® (Mycotech, Butte) and Naturalis L® (Troy Biosciences). These products are registered against sucking pests such as whitefly, aphids, thrips, mealybugs, leafhoppers, and weevils. Studies also show that *B. bassiana* is virulent against *Lygus hesperus* Knight (Hemiptera: Miridae), a major pest of alfalfa and cotton in the USA (Noma and Strickler 2000).

Viral Biopesticides

Like bacteria and fungi, viral biopesticides play a significant role in antagonizing pathogens especially bacteria in the form of bacteriophages. Apart from it, viruses are host specific, infecting only one or a few closely related species, thus offering minimal off-target impacts (Cory and Myers 2003; England et al. 2004; Raymond et al. 2005; Hewson et al. 2011). A bacteriophage is a virus that infects bacterial cell walls. If the virus attacks bacteria that cause plant disease, it can be used as a pesticide. A large number of phage pesticides are currently used under commercial trade names and sold in the markets. Patent protection and intellectual property are important factors in the commercialization of phage pesticides. The concept of phage therapy has existed for over 90 years, and multiple companies have acquired patents and established commercial platforms for using them (Gill et al. 2007). A leading company of the USA, Omnilytics, has developed a range of phage products for the control of *Xanthomonas campestris* pv. vesicatoria, for the treatment of bacterial spot of tomatoes and peppers, and *P. syringae* pv. tomato, which is the causative agent of bacterial speck on tomatoes (Frampton et al. 2012; Schofield et al. 2012).

Baculovirus is the main virus that is commercially used for designing phage pesticides. Since the start of their commercial use, baculoviruses have been tested extensively to assess their safety in order to meet registration requirements (reviewed in Burges et al. 1980a, b; Gröner 1986; Ignoffo 1975). Baculoviruses develop in the nuclei of the host insect cells. When ingested by the host insect, infectious virus particles are liberated internally and become active. Once in the larval gut, the virus's protein overcoat quickly disintegrates, and the viral DNA proceeds to infect digestive cells. Within a few days, the host larvae are unable to digest food and so weaken and die (Thakore 2006). Baculoviruses are particularly attractive for use as biopesticides due to their high host specificity. Each virus only attacks particular species of insects, and they have been shown to have no negative impacts on plants, mammals, birds, fish, or nontarget insects (D'Amico 2007). Baculoviruses can also cause sudden and severe outbreaks within the host population for complete control of the disease (Sylvar 2008). Another major advantage of baculoviruses is that in some cases, they can replace and serve as an alternative to the antibiotics and chemical pesticides (O'Brien et al. 2009).

As of 2010, over 24 baculovirus species have been reported to be registered for use in insect pest management throughout the world (Kabaluk et al. 2010). The market share of baculoviruses is 6 % of all microbial pesticides (Quinlan and Gill 2006; Marrone 2007), and millions of hectares have been treated with registered baculovirus products over the years (Szewczyk et al. 2009; Kabaluk et al. 2010; Moscardi et al. 2011). Despite many years of use and testing against nontarget organisms, no adverse effects have ever been attributed to baculoviruses (McWilliam 2007).

Biopesticides: Global Scenario

A large number of crop pests cause about 40 % reduction in the world's crop yield (Oerke et al. 1994), and control measures adopted by using synthetic chemicals alone have remained formidable as the data suggests that approximately 5.6 billion pounds of pesticide are used worldwide and are responsible for the unbalancing of our environment (Alavanja 2009). Whereas application of biopesticides showed lesser or no toxicity to crops and is considered environment friendly, these are not globally as dominating as synthetics. Application and development trend of biopesticides has been reviewed by Leng et al. (2011). Worldwide, approximately 1,400 biopesticide products were being sold (Marrone 2007). Table 2.1 depicts a comprehensive list of commercially available biopesticides in the markets around the globe. These products are commercially successful and widely available as liquid concentrates, wettable powders, and ready-to-use dusts and granules. Among them, bacterial products are more frequently used (Fig. 2.1) especially those from Bt (Lisansky 1997). Production of Bt always remained on priority in biopesticide industry, and currently it is the main bacterium being used in agricultural pest control (Brar et al. 2006; Ali et al. 2008). Its firm position in biopesticide industry is indicated by the fact that more than 53 % of the world biopesticide market is occupied by about 200 Bt-based products (CABI 2010), and almost 50 % of this is consumed by America particularly in the USA and Canada (Guerra et al. 2001). Data on microbial biopesticide agents from Agriculture and Agri-Food Canada (Kabaluk and Gazdik 2005) and the USEPA indicate that more than 200 products are being sold in the USA, compared to only 60 comparable products in the EU. In the UK, only 5 microbial products were reported to be sold, compared to 10 in Germany and 15 each in France and the Netherlands (Chandler et al. 2008). Till 2003, the largest market shares in biopesticide belonged to North America with 44 %, followed by Europe with 20 %, Asia (13 %), Oceania (11 %), Latin America (9 %), and lowest for Africa (3 %) (Fig. 2.2). In this section, we discuss the continent-wise scenario of biopesticides.

North America

North America leads in market share of biopesticides and covers 44 % of it. In Canada alone, end-user sales of pesticides were valued at $1.4 billion in 2010, and of this, microbial pesticides represented about 0.5 % ($7.4 million), with 88 % of microbials represented by Bt ($6 million for use in forestry; $500,000 for use in agriculture), 6.7 % ($500,000) for other bacteria, 0.67 % ($50,000) for viruses, 0.67 % ($50,000) for fungi, and 4.1 % ($300,000) for nematodes (CPL Business Consultants 2010). Numerous universities across Canada are actively engaged in the research and development of biopesticides ranging from botanical to microbial pesticides for control of insects, weeds, and fungi. In the USA, the first registered microbial pesticide was prepared using *Bacillus popilliae* (*Paenibacillus popilliae*) in 1948 for the control of the Japanese beetle (Schneider 2006). Whereas a commercially unsuccessful entomopathogenic fungus (*Hirsutella thompsonii*)-based product Mycar was first registered for control of citrus rust mites, for which approval was granted to Abbott Laboratories in 1981 (McCoy 1996). In the USA, EPA is the sole agency responsible for encouraging development and use of biopesticides. Biopesticides and Pollution Prevention Division (under the Pesticide Programs) was established in 1994 in the USA with the goal of reducing risks associated with pesticide use in agricultural and nonagricultural settings and advocates adoption of biopesticides. In the USA, pesticide has to pass stringent regulations before its marketing, and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) does this job along with EPA, assessing carcinogenic risks or short-term mutagenicity assays to ensure that pesticide can be used with a reasonable certainty, and it will not harm human health or the environment. Such stringency in regulation created a positive pressure on growers to adopt biopesticides.

Table 2.1 Commercially available biopesticides in the global market

Category of biopesticide	Products common name or trade name	Targets
The USA		
Bactericides		
A. radiobacter k84	Galltrol – A	Crown gall disease
P. agglomerans C9-1	BlightBan C9-1	Fire blight
P. agglomerans E325	Bloomtime	Fire blight
Bacteriophage of *P. syringae* pv. Tomato	AgriPhage	Bacterial speck
Bacteriophage of *X. campestris* pv. Vesicatoria	AgriPhage	Bacterial spot
Fungicides		
B. licheniformis SB3086	EcoGuard	Fungal diseases
Bacillus mycoides isolate J	BacJ	Cercospora
B. pumilus GB 34	GB34	Seedling diseases – *Pythium* and *Rhizoctonia*
B. pumilus QST 2808	Sonata	Powdery mildew, downy mildew, and rusts
	Ballad Plus	
B. subtilis GB03	Companion	*Fusarium*, *Pythium*, *Rhizoctonia*
	Kodiak	
B. subtilis MBI 600	Histick N/T	Damping off
	Pro-Mix with Biofungicide	
B. subtilis subsp. amyloliquefaciens FZB24	Taegro	*Fusarium* and *Rhizoctonia* wilt diseases
P. aureofaciens Tx-1	Spot-Less	Turf fungal diseases
Pseudomonas chlororaphis 63–28	At-Eze	Soil and seed-borne fungi
P. syringae ESC 10	Bio-Save 10LP	Postharvest diseases
P. syringae ESC 11	Bio-Save 11LP	Postharvest diseases
Streptomyces griseoviridis K61	Mycostop	Fungi causing damping off, stem, and crown rots
	Biofungicide	
	Mycostop Mix	
S. lydicus WYEC108	Actinovate	Fungi causing damping off, stem and crown rots
	Actino-Iron	
Ampelomyces quisqualis M10	PowderyGon	Powdery mildew
Aspergillus flavus AF36	*Aspergillus flavus* AF36	*Aspergillus flavus* producing aflatoxin
A. flavus NRRL 21882	Afla-guard	*Aspergillus flavus producing aflatoxin*
C. minitans CON/M/91–08	Contans	*Sclerotinia minor*, *Sclerotinia sclerotiorum*
Gliocladium catenulatum J1446	Prestop	Seed-borne and soil-borne diseases
M. albus QST 20799	Arabesque	Postharvest diseases
Pseudozyma flocculosa PF-A22 UL	Sporodex	Powdery mildew
Trichoderma asperellum ICC 012 and *T. harzianum* (*gamsii*) ATCC080	Tenet	Soil-borne diseases
	Bioten	
	Remedier	
T. harzianum ATCC 20476	Binab	Wound healing
T. harzianum Rifai T-22	PlantShield	Seed and foliar diseases
	RootShield	
	T-22 Planter box	
T. harzianum T-39	Trichodex	Soil and foliar diseases

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
Trichoderma polysporum ATCC 20475	Binab T	Soil and foliar diseases
Ulocladium oudemansii U3	BOTRY-Zen	Botrytis and *Sclerotinia*
Verticillium albo-atrum WC S850	DutchTrig	Dutch elm disease
Bacteriophage of *P. syringae* pv. tomato	AgriPhage	Tomato leaf spot
Candida oleophila strain O	NEXY	Postharvest fruit molds
Fungicides/bactericides		
B. subtilis QST713	Serenade	Foliar fungal and bacterial diseases
Herbicides		
Bacillus cereus BP01	MepPlus	Plant growth regulator
Alternaria destruens 059	Smolder	Herbicide – dodder
Chondrostereum purpureum PFC 2139	Chontrol Paste	Herbicide – stump sprout inhibitor
Colletotrichum gloeosporioides f.sp. aeschynomene ATCC 202358	LockDown	Herbicide – northern Jointvetch
Puccinia thlaspeos woad (dyer's woad rust)	Woad Warrior	Herbicide – Dyer's woad
Insecticides		
B. popilliae	Milky Spore Powder	Japanese beetle grubs
Bacillus sphaericus Serotype H5a5b strain 2362 ATCC1170	VectoLex	Mosquito larvae
B. thuringiensis subsp. aizawai NB200	Florbac	Moth larvae
B. thuringiensis subsp. israelensis	BMP	Mosquito and blackflies
B. thuringiensis subsp. israelensis EG2215	Gnatrol	Mosquito, flies
	Aquabac	
B. thuringiensis subsp. aizawai delta-endotoxin in killed *P. fluorescens*	M-Trak	Colorado potato beetle
B. thuringiensis subsp. aizawai GC-91	Agree WG	Plutella
B. thuringiensis subsp. kurstaki	Thuricide Forestry	Lepidopteran larvae
	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	
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

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
B. thuringiensis subsp. kurstaki EG7826	Lepinox WDG	Lepidopteran larvae
B. bassiana 447	Baits Motel Stay-awhile	Ants
B. bassiana ATCC 74040	Naturalis L	Various insects
B. bassiana GHA	Mycotrol ES	Various insects
	Mycotrol O	
	Botanigard 22WP	
	BotaniGard ES	
B. bassiana HF23	balEnce	Housefly
M. anisopliae F52	Tick-Ex	Ticks and grubs
Paecilomyces fumosoroseus Apopka 97	PFR-97	Whitefly and thrips
Nosema locustae	Nolo-Bait	Grasshopper and crickets
	Semaspore Bait	
Anagrapha falcifera NPV	CLV-LC	Lepidopteran larvae
Cydia pomonella GV	CYD-X	Virus codling moth
Gypsy moth NPV	Gypchek	Gypsy moth
H. zea NPV (previously *Heliothis zea* NPV)	GemStar	Cotton bollworm, tobacco, budworm
Indian meal moth GV (*Plodia interpunctella* GV)	FruitGuard	Indian meal moth
Mamestra configurata NPV (107308)	Virosoft	Bertha armyworm
Spodoptera exigua NPV	Virus Spod-X	Beet armyworm
Saccharomyces cerevisiae	Bull Run	Fly attractant
Nematicides		
Bacillus firmus I-1582	BioNem	Nematodes
Pasteuria usgae	Econem	Nematodes
Myrothecium verrucaria	DiTera	Nematodes
Paecilomyces lilacinus 251	MeloCon WG	Nematodes
Virucides		
Zucchini yellow mosaic virus – weak strain	AgroGuard-Z	Zucchini yellow mosaic
Europe		
Aureobasidium pullulans	Blossom Protect	Fire blight, postharvest diseases
Phlebiopsis gigantea (several strains)	Rotstop	Conifer root rots
P. chlororaphis	Cedomon, Cerall	*Pyrenophora teres*, *P. graminea*, *Tilletia caries*, *Septoria nodorum*, *Fusarium* spp.
Pseudomonas sp. DSMZ 13134	Proradix	Root rots
S. griseoviridis K61	Mycostop	*Fusarium* wilt, *Botrytis* gray mold, root rot, stem rot, stem end rot, damping off, seed rot, soil-borne damping off, crown rot, *Rhizoctonia*, *Phytophthora*, wilt, seed damping off, early root rot
A. quisqualis AQ10	AQ10	*Leaf disease*
C. oleophila strain O		Postharvest disease
C. minitans CON/M-91–05	Contans WG	*Sclerotinia sclerotiorum*, *S. minor*
G. catenulatum J1446	Prestop, Prestop mix	Damping off, gummy stem blight, gray mold, root rot, stem rot, wilt, storage diseases, foliar diseases, seed rot

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
P. flocculosa PF-A22 UL	Sporodex	Powdery mildew
Pythium oligandrum	Polyversum	Root rots
Trichoderma asperellum (ICC012) (T25) (TV1) (formerly *T. harzianum*)	Tenet	Fungal infections (*Pythium*, *Phytophthora*, *Botrytis*, *Rhizoctonia*)
Trichoderma atroviride IMI 206040 (formerly *T. harzianum*)	Binab T Pellets	*Botrytis cinerea*, pruning wound infection *Chondrostereum purpureum*
T. atroviride I-1237	Esquive	Fungal infections (*Pythium*, *Phytophthora*, *Botrytis*, *Rhizoctonia*)
Trichoderma gamsii (formerly *T. viride*) (ICC080)	Remedier	Fungal infections (*Pythium*, *Phytophthora*, *Botrytis*, *Rhizoctonia*)
T. harzianum Rifai T-22 ITEM 108 or KRL-AG2	Trianum P	Root diseases
T. harzianum Rifai T-39 (IMI 206039)	Trichodex	*Botrytis cinerea*, *Colletotrichum* spp., *Fulvia fulva*, *Monilia laxa*, *Plasmopara viticola*, *Pseudoperonospora cubensis*, *Rhizopus stolonifer*, *Sclerotinia sclerotiorum*
	Rootshield	
T. polysporum and *T. harzianum*	Binab T Vector	Fungal pathogens, fairy ring, *Botrytis*, *Verticillium*, *Pythium*, *Fusarium*, *Phytophthora*, *Rhizoctonia*, *Didymella*, *Chondrostereum*, *Heterobasidion*
V. albo-atrum (WCS850) (formerly *Verticillium dahliae*)	Dutch Trig	Dutch elm disease
Fungicides/bactericides		
B. subtilis QST 713	Serenade	Fire blight, *Botrytis* spp.
Insecticides		
B. thuringiensis subsp. *aizawai* GC-91	Turex	Lepidoptera pests
B. thuringiensis subsp. *israelensis* AM65	VectoBac	Sciarids
B. thuringiensis subsp. *kurstaki* HD-1	Dipel WP	Lepidoptera pests
B. thuringiensis subsp. kurstaki ABTS 351, PB 54, SA 11, SA12, and EG 2348	Batik	Lepidoptera pests
	Delfin	
B. thuringiensis subsp. *kurstaki* BMP 123	BMP 123	Lepidoptera pests
	Prolong	
B. thuringiensis subsp. *tenebrionis* NB 176	Novodor	Coleoptera pests
B. bassiana ATCC 74040	Naturalis L	Thrips, whitefly, mites
B. bassiana GHA Fungus	Botanigard	Whiteflies, aphids, thrip
Lecanicillium muscarium (Ve6) (former *Verticillium lecanii*)	Mycotal, Vertalec	Whiteflies, thrips, aphids (except the Chrysanthemum aphid: *Macrosiphoniella sanborni*)
P. fumosoroseus Apopka 97	Preferal WG	Greenhouse whiteflies (*Trialeurodes vaporariorum*)
P. fumosoroseus Fe9901	Nofly	Whiteflies
Adoxophyes orana BV-0001 GV	Capex	Summer fruit tortrix (*Adoxophyes orana*)
Cydia pomonella GV	BioTepp	Codling moth (*Cydia pomonella*)
Spodoptera exigua NPV	Spod-X GH	*Spodoptera exigua*

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
Nematicides		
P. lilacinus PL 251	BioAct WG	Common plant parasitic nematodes
Virucides		
Zucchini Yellow Mosaic Virus, weak strain Virus	Curbit	Yellow mosaic virus
China		
Bactericides		
A. radiobacter	Trade name not available	Crown gall
Bacillus polymyxa	Trade name not available	Crown gall
Bacillus sphaericus	Trade name not available	Crown gall
Fungicides		
B. cereus	Trade name not available	Bacterial wilt, sheath blight/rice false smut, bacterial wilt
B. licheniformis		Downy mildew, *Fusarium* wilt
B. subtilis	Trade name not available	Bacterial wilt, root rot, tobacco black shank, rice blast, rice false smut
Trichoderma spp.		Fungus downy mildew, *Rhizoctonia cerealis*, gray mold
Fungicides/bactericides		
P. fluorescens	Trade name not available	Bacterial wilt, root rot
Insecticides		
B. thuringiensis subsp. aizawa	Trade name not available	Lepidopteran pests
B. thuringiensis subsp. israelensis	Trade name not available	Lepidopteran pests
B. thuringiensis subsp. kurstaki		Lepidopteran pests
Pseudomonas alcaligenes	Trade name not available	Locusts, grasshoppers
B. bassiana		*Monochamus alternatus*, *Dendrolimus punctatus*
Conidobolus thromboides	Trade name not available	Aphids
M. anisopliae		Cockroaches, grasshoppers, locusts
P. lilacinus	Trade name not available	Nematodes
Pochonia chlamydosporia		Nematodes
Dendrolimus cytoplasmic polyhedrosis virus	Trade name not available	Virus Caterpillars
NPV, *Ectropis obliqua hypulina* NPV, *Laphygma exigua* NPV, *Prodenia litura* NPV, *Buzura suppressaria* NPV, *Gynaephora ruoergensis* NPV, *Mythimna separata* NPV	Trade name not available	Virus Beet armyworm, lepidoptera, looper, *H. armigera*, *Laphygma exigua*
Periplaneta fuliginosa densovirus virus	Trade name not available	Cockroaches
Pieris rapae GV, *Mythimna separata* GV, *Plutella xylostella* GV	Trade name not available	*Pieris rapae*, *Plutella xylostella*
Japan		
Insecticides (bacterial, fungal, viral, parasitic nematodes)		
B. thuringiensis kurstaki	Toarowaa Esmark Guardjet, Dipol, Tuneup Fivestar BioMax DF	Lepidopteran larvae

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
B. thuringiensis aizawai	Quark XenTari Florbac Sabrina	Lepidopteran larvae
B. thuringiensis aizawai +kurstaki	Bacilex	Lepidopteran larvae
B. thuringiensis japonensis	BuiHunter	Cockchafers and white grubs
B. bassiana	BotaniGard	Thrips, whiteflies, diamondback moth
P. fumosoroseus	Preferd	Whitefly, aphids
Lecanicillum longisporum	Vertalec	Aphids
Adoxophyes orana GV+Homona magnanima GV	Hamaki-Tenteki	*Adoxophyes honmai* and *Homona magnanima*
Steinernema carpocapsae	Bio Safe	Weevils, black cutworm, common cutworm, peach fruit moth
India		
Fungicide		
P. fluorescens	ABTEC Pseudo	Plant soil-borne diseases
	Biomonas	
	Esvin Pseudo	
	Sudo	
	Phalada 104PF	
	Sun Agro Monus	
	Bio-cure-B	
A. quisqualis	Bio-Dewcon	Powdery mildew
T. harzianum	Biozim	Soil-borne pathogens
	Phalada 105	
	Sun Agro Derma H	
T. viride	Monitor, Trichoguard	Soil-borne pathogens
	NIPROT	
	Bioderma	
	Biovidi	
	Eswin Tricho	
	Biohit	
	Tricontrol	
	Ecoderm	
	Phalada 106TV	
	Sun Agro Derma	
	Defense SF	
Fungicides/bactericides		
B. subtilis		Soil-borne pathogens
Insecticides		
B. thuringiensis subsp. israelensis	Tacibio, Technar	Lepidopteran pests
B. thuringiensis subsp. Kurstaki	Bio-Dart	Lepidopteran pests
	Biolep	
	Halt	
	Taciobio-Btk	

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
B. bassiana	Myco-Jaal	Coffee berry borer, diamondback moth, thrips, grasshoppers, whiteflies, aphids, codling moth
	Biosoft	
	ATEC Beauveria	
	Larvo-Guard	
	Biorin	
	Biolarvex	
	Biogrubex	
	Biowonder	
	Veera	
	Phalada 101B	
	Bioguard	
	Bio-power	
M. anisopliae	ABTEC	Coleoptera and lepidoptera, termites, mosquitoes, leafhoppers, beetles, grubs
	Verticillium	
	Meta-Guard	
	Biomet	
	Biomagic	
	Meta	
	Biomet	
	Sun Agro Meta	
	Bio-Magic	
P. fumosoroseus	Nemato-Guard	Whitefly
	Priority	
P. lilacinus	Yorker	Whitefly
	ABTEC	
	Paceilomyces	
	Paecil	
	Pacihit	
	ROM biomite	
	Bio-Nematon	
Verticillium lecanii	Verisoft	Whitefly, coffee green bug, homopteran pests
	ABTEC	
	Verticillium	
	Vert-Guard	
	Bioline	
	Biosappex	
	Versitile	
	Ecocil	
	Phalada 107 V	
	Biovert Rich	
	ROM Verlac	
	ROM Gurbkill	
	Sun Agro Verti	
	Bio-Catch	

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
H. armigera NPV	Helicide	*H. armigera*
	Virin-H	
	Helocide	
	Biovirus-H	
	Helicop	
	Heligard	
Spodoptera litura NPV	Spodocide	*S. litura*
	Spodoterin	
	Spodi-cide	
	Biovirus-S	
Nematicides		
Verticillium chlamydosporium		Nematodes
Australia		
Fungicide		
P. fluorescens	ABTEC Pseudo	Plant soil-borne diseases
	Biomonas	
	Esvin Pseudo	
	Sudo	
	Phalada 104PF	
	Sun Agro Monus	
	Bio-cure-B	
A. quisqualis	Bio-Dewcon	Powdery mildew
T. harzianum	Biozim	Soil-borne pathogens
	Phalada 105	
	Sun Agro Derma H	
T. viride	Monitor, Trichoguard	Soil-borne pathogens
	NIPROT	
	Bioderma	
	Biovidi	
	Eswin Tricho	
	Biohit	
	Tricontrol	
	Ecoderm	
	Phalada 106TV	
	Sun Agro Derma	
	Defense SF	
Fungicides/bactericides		
B. subtilis		Soil-borne pathogens
Insecticides		
B. thuringiensis subsp. israelensis	Tacibio, Technar	Lepidopteran pests
B. thuringiensis subsp. Kurstaki	Bio-Dart	Lepidopteran pests
	Biolep	
	Halt	
	Taciobio-Btk	

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
B. bassiana	Myco-Jaal	Coffee berry borer, diamondback moth, thrips, grasshoppers, whiteflies, aphids, codling moth
	Biosoft	
	ATEC Beauveria	
	Larvo-Guard	
	Biorin	
	Biolarvex	
	Biogrubex	
	Biowonder	
	Veera	
	Phalada 101B	
	Bioguard	
	Bio-power	
M. anisopliae	ABTEC	Coleoptera and lepidoptera, termites, mosquitoes, leafhoppers, beetles, grubs
	Verticillium	
	Meta-Guard	
	Biomet	
	Biomagic	
	Meta	
	Biomet	
	Sun Agro Meta	
	Bio-Magic	
P. fumosoroseus	Nemato-Guard	Whitefly
	Priority	
P. lilacinus	Yorker	Whitefly
	ABTEC	
	Paceilomyces	
	Paecil	
	Pacihit	
	ROM biomite	
	Bio-Nematon	
V. lecanii	Verisoft	Whitefly, coffee green bug, homopteran pests
	ABTEC	
	Verticillium	
	Vert-Guard	
	Bioline	
	Biosappex	
	Versitile	
	Ecocil	
	Phalada 107 V	
	Biovert Rich	
	ROM Verlac	
	ROM Gurbkill	
	Sun Agro Verti	
	Bio-Catch	

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
H. armigera NPV	Helicide	*H. armigera*
	Virin-H	
	Helocide	
	Biovirus-H	
	Helicop	
	Heligard	
S. litura NPV	Spodocide	*S. litura*
	Spodoterin	
	Spodi-cide	
	Biovirus-S	
Nematicides		
Verticillium chlamydosporium		Nematodes
Bactericides		
A. radiobacter	NoGall	Crown gall disease
Fungicides		
T. harzianum	Trichodex	*Botrytis* spp.
Insecticides		
B. sphaericus	VectoLex	Mosquito larvae
B. thuringiensis subsp. a*izawai*	Agree, Bacchus, XenTari	Lepidoptera larvae
B. thuringiensis subsp. israelensis	Aquabac, BTI, Teknar, Vectobac	Mosquito larvae
B. thuringiensis subsp. kurstaki	Biocrystal, Caterpillar, Killer, DiPel, Costar, Delfin, Full-Bac WDG	Lepidoptera larvae
M. anisopliae	BioCane, Granules	Gray-backed cane grub (scarabs)
M. anisopliae subsp. *acridum*	Green Guard	Locusts and grasshoppers
M. flavoviride	Chafer Guard	Redheaded pasture cockchafer
H. armigera NPV	Heliocide	*Helicoverpa* spp.
	Vivus Gold	
	Vivus Max	
H. zea NPV	Gemstar	*Helicoverpa* spp.
	Vivus	
Africa		
Bactericides	**Products**	**Targets**
A. radiobacter	Crown Gall Inoculant	Crown gall
Fungicides		
B. subtilis 101	Shelter	Root and leaf diseases
B. subtilis 102	Artemis	Root and leaf diseases
B. subtilis 246	Avogreen	Root and leaf diseases
B. subtilis QST 713	Serenade	*Botrytis* spp.
A. quisqualis AQ10	Bio-Dewcon	Powdery mildew

(continued)

Table 2.1 (continued)

Category of biopesticide	Products common name or trade name	Targets
T. harzianum	Eco-77	Root diseases
	Eco-T	
	Promot	
	Romulus	
	Rootgard	
	Trichoplus	
	Trykocide	
T. harzianum 39	Trichodex	Root diseases
T. harzianum DB103	T-Gro	Root diseases
Fungicides/bactericides		
B. subtilis	Defender	Soil-borne fungi and bacteria
Insecticides		
B. thuringiensis subspp. aizawai and kurstaki	Agree	Lepidoptera larvae
B. thuringiensis subsp. israelensis	VectoBac	Mosquito
B. thuringiensis subsp. kurstaki	DiPel	Lepidoptera larvae
	Rokur	
	Thuricide	
B. thuringiensis subsp. kurstaki H7	Florbac WG	Lepidoptera larvae
B. bassiana	Bb Plus, Bb weevil, Sparticus	Thrips, weevils, whiteflies
M. anisopliae subsp. acridum IMI 330 189	Green Muscle	Locust
GV	Trade name not available	Lepidoptera larvae
Pseudomonas resinovorans bacteriophage	Agriphage	Insect pest control
Nematicides		
P. lilacinus	Bio-Nematon	Nematodes
P. lilacinus 251	PL Plus	Nematodes

Source: Kunimi (2007) and Kabaluk et al. (2010)

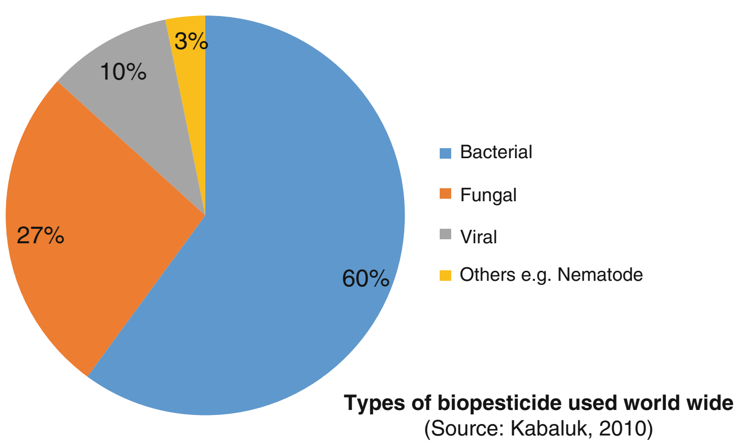

Fig. 2.1 Global biopesticide market based on types of microbes used

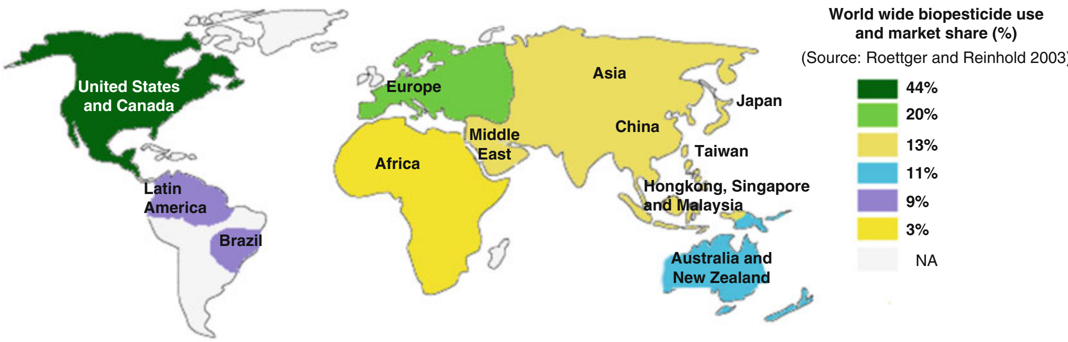

Fig. 2.2 Global biopesticide use and market

Keeping in mind the importance of minor crops (defined as any crop grown on 300,000 acres or less), the US Department of Agriculture (USDA) initiated the Interregional Research Project No. 4, commonly known as IR-4. The USDA IR-4 program has provided grant funding to key influencers such as land-grant university extension specialists to demonstrate with the end user the performance of biopesticides in realistic programs with conventional pesticides (Radcliffe et al. 2009). Overall progress of biopesticides in the USA can be considered as satisfactory. According to EPA data in the USA, 102 microbials, 52 biochemicals, and 48 semiochemicals are being used as biopesticides (USEPA 2011).

Europe

Europe ranks second in biopesticide production. The largest individual European biopesticide market is Spain, followed by Italy and France (Business Wire 2010). The first Bt-based product (Thuricide) was approved in Europe in 1964, whereas first registration for an entomopathogenic fungus *L. longisporum* was given in 1981 to Tate and Lyle in the UK (Quinlan 1990). Europe also belongs to continents where the MRL (Maximum Residue Level) regulations in food products have been strictly decided (Regulation (EC) 396/2005), and the European Food Safety Authority (EFSA) has an important role in this system. EFSA provides independent scientific advice to support the risk managers (EU institutions and Member States) in defining appropriate regulatory frameworks and making decisions to protect consumers. These may involve adopting or revising European legislation on food or feed safety or deciding whether to approve regulated substances such as pesticides and food additives, and if so in which foods or crops and at what levels. This resulted in farmers to produce crop having very less concentration of pesticide or with no detectable limit. In this residue-controlling movement the Ministry of Food, Agriculture, and Fisheries in France launched the program "Ecophyto 2018," in 2008, for a 50 % reduction in the use of pesticides by 2018 (agriculture.gouv.fr/IMG/pdf/PLAN_ECOPHYTO_2018_eng.pdf). In 2011, Europe implemented the Plant Protection Products Regulation (www.eppo.int/PPPRODUCTS/information/new_eu_regulations.htm), and according to that, any crop protection product validates not only that it is effective but also that it should be risk free to humans and to the environment. This made 74 % of all commercial pesticides illegal, as only 26 % of substances passed the new stringent tests, biopesticides being among them (www.pangaeaventures.com/blog/biopesticides-the-next-crop-of-cleantech-home-runs). Currently, most of the European consumers are demanding production of food that hasn't been treated with conventional pesticides; that is why in the present time, Europe has set the standard for biopesticides use. In spite of the stark law on residue control, development of new biopesticide faces hurdle of registration which may take at least 5 years and cost up to € 0.5 million. Presently there are 68 biopesticide active substances registered in

Europe that consist of 34 microbials, 11 biochemicals, and 23 semiochemicals (EUPD 2010). The proportion of the European microbial pesticide market taken by *B. thuringiensis*-based products has declined from an estimated 90 % in 2000 to 50.6 % in 2008 mainly because of the arrival of other BCAs (Business Wire 2010). The largest increases since 2005 were seen in non-Bt bacteria, notably *B. subtilis*, and in fungal-based products, including *C. minitans* and *Trichoderma*. There were also significant increase in viral sales and a steady rise in the nematode market (Business Wire 2010).

Asia

Asia is the largest continent in the world and known for its diverse biodiversity. In Asia, the economy depends heavily on agriculture. Using biopesticides in food crops such as rice, maize, and vegetables is increasing gradually. Rice is the main staple hence much of the biocontrol experimentation and practical use was done on this crop. China is one of the most populated countries in the world, and it is producing biopesticides since 1960, most of them being in the form of unformulated dried cultures (Xu et al. 1987). Biopesticide application was done in 800,000 ha in 1972 which reached 27,000,000 ha in 2000 (Ye and Chen 2002; Zhang 2002; Yang 2007). Till 2008, there were 327 biopesticides registered in China. Among these, 270 bacterial biopesticides are obtained from 11 microbial species (mostly Bt), 22 registered fungal biopesticides from 6 fungal species, and 35 registered viral biopesticides, 14 of which are developed from *Heliothis armigera* NPV (ICAMA 2008).

Japan is one of the pioneer countries as far as the use of biopesticides is considered. In Japan, registration process for Bt was a typical case (Aizawa and Ishiwata 2001) as the earlier application had posed a negative impact on sericulture. In 1972, a study committee on Bt products was established for studying the effects of Bt products on silkworm rearing in sericulture (Aizawa and Fujiyoshi 1973), and after 7 years, the committee concluded that Bt products would not pose a threat to silkworm rearing if farmers were prevented from spraying Bt products on mulberry fields (Study Committee on *Bacillus thuringiensis* Products 1984). Finally, the first Bt registered product was launched in 1981 (Kunimi 2007) and later formulated products of Bt aizawai, Bt kurstaki, and Bt japonensis were also introduced (Ohba et al. 1992). NPV was first time used to control cabbage armyworm, *Mamestra brassicae*, in 1962 (Kunimi 1998). Entomopathogenic fungus *B. bassiana* was also tried to control pine caterpillar (*Dendrolimus spectabilis*) in 1933 by Hidaka (1933). In the last few years, Japanese research in biocontrol field has resulted in the identification and characterization of several new insect pathogens, delivery systems, and formulation development, but the sale of microbial-based products remained less satisfactory, even less than 2 % of all insecticides sold (Kunimi 2007).

In India, biocontrol concept was in practice ever since neem was used as an alternative to chemical pesticides. Farmers have been using neem not only for vegetable protection but also in various other medically imported applications. Evidence of using insects and birds for pest eradication is also found (Subramaniam 1952). In India, microbial-based pesticides evolved as an emergent need when chemical insecticides failed to control *Helicoverpa armigera*, *S. litura*, and other pests of cotton (Armes et al. 1992; Kranthi et al. 2002). In India, the first time commercial production of biocontrol agents was started by Bio-Control Research Laboratories (BCRL), a division of Pest Control (India) Limited, under contract with Plant Protection Research Institute (PPRI) (Manjunath et al. 1992). The rise of biopesticides in India is being encouraged by the government as part of the integrated pest management (IPM) program. The Ministry of Agriculture and the Department of Biotechnology are largely responsible for supporting the production and application of biopesticides, and most of biopesticides are being supplied free of cost by the research agencies to farmers through extension services (Alam 1994). In the last few years, microbes exhibiting good biocontrol potential have been discovered by many workers and are commercially exploited for large-scale biopesticide development (Rabindra 2001; Ignacimuthu et al. 2001; Koul et al. 2003; Ranga Rao et al. 2007). Most of the products are from antagonistic fungi (especially *Trichoderma* spp.) and bacteria (especially Bt and *P. fluorescens*), whereas viral biopesticides consist of NPV and granuloviruses (GV) (Rabindra 2005). But large-scale production poses certain difficulties, and lesser developed technology is the main hurdle for industrial production. Hence, most of the products are being produced at small-scale facilities for local use only, mostly by sugar mills and cooperatives, state agricultural departments, IPM centers, and agricultural universities. By 2006, only 12 biopesticides (that of Bt, *Trichoderma*, *Pseudomonas*, and *Beauveria* species) had been registered, but 194 substances were listed as chemical pesticides (Gupta 2006). However, biopesticides consumption has increased in India as there was 219 metric tons (MT) of biopesticide used in 1996–1997 which increased to 683 MT in 2000–2001, whereas load of chemical pesticides had declined from 56,114 MT to 43,584 MT in the same years (Shukla and Shukla 2012). India is still facing problems associated with production, and quality of the products are not up to the desired level because of which farmers are not very enthusiastic for biopesticides in comparison to chemical pesticides (Gupta and Dikshit 2010).

Bt was the first biopesticide product to be introduced and commercialized into the Thai market in 1965 (Rushtapakomchai 2003). But it was largely neglected by farmers as they did not know much about Bt due to its slow and highly selective action (Rushtapakomchai 2003). Finally in 1969, Bt kurstaki was introduced to control lepidopterous larvae of cruciferous crops (Prasetphol et al. 1969; Vattanatangum 1989). Active research on biopesticide started in 1980 to produce products containing Bt, NPV, and fungi (Jones et al. 1993). The promotion of biopesticide is going on in Thailand, and by 2003 there were six major biopesticides in the market from Bt (subspecies kurstaki, aizawai, and tenebrionis), fungal products of *T. harzianum*, entomopathogenic fungi, entomopathogenic nematodes, and NPV (Rushtapakomchai 2003). Although the production is increasing, it is not enough to fulfill the demand of the whole country, whereas poor quality of some of the noncommercial biopesticides is also a cause for concern (Warburton et al. 2002).

In South Korea, microbial pest control was initiated in 1970 and involved the use of entomopathogenic viruses, bacteria, fungi, and nematodes to control pests in forestry, agriculture, and golf courses, but it took many years when the first commercial biopesticide, "Solbichae" (a Bt subsp. aizawai), was registered in 2003 to control diamondback moth and beetle armyworm in Chinese cabbage (Jeong et al. 2010). By 2009, 34 microbial pesticide products were registered to control insect pests and plant diseases in Korea (Jeong et al. 2010).

Australia

Microbial control first began in the late 1960s with the GV of codling moth (*Cydia pomonella*) and nucleopolyhedrosis virus (NPV) of *Helicoverpa zea*. Initially, limited success was observed in field trials in comparison with their chemical counterparts, but GV proved to be effective against potato tuber moth (*Phthorimaea operculella*) (Reeda and Springetta 1971). A vast variety of products have been registered, but among them *B. thuringiensis* subsp. *kurstaki* (Btk) is the most famous product, and in 1987–1988 when there was increased incidence of cotton pest, Btk-based products accounted for a 2 % market share of all the insecticides (Powles and Rogers 1989; Fitt 1994, 2004). Fungal biocontrol research was mainly directed toward *Metarhizium* to control a wide range of insects (Milner and Jenkins 1996) but especially its effectiveness against locust and grasshopper was of much interest and its oil-based formulation with high persistence in soil made it very popular in Australia (Ibrahim et al. 1999; Milner et al. 1997; Lomer 2001). BioGreen was first registered and commercially produced *Metarhizium*-based product. After the success of BioGreen, other *Metarhizium*-based products also came up and showed remarkable response in biocontrol of crop diseases (Milner 2000).

Latin America

There is a growing trend of using biopesticides in organic culture in Latin America, especially at the local level production for indigenous use has increased meaningfully by the involvement of the local government and NGOs. In Latin America, a proportion of Bt-based products cover about 40 % of the market (CPL Business Consultants 2010). In Argentina, Bt products were first used in 1950 against *Colias lesbia* in alfalfa (Botto 1996). The first virus-based product was registered in 2000 by Agro Roca, and the fungal product based on *B. bassiana* for controlling *Triatoma infestans* and *Musca domestica* was first registered by Alves et al. (2008). The use of biopesticides has risen in Brazil, and by 2010 approximately 3 million hectares of agricultural cropland were being treated annually with microbial pesticides (Kabaluk et al. 2010). The use of Bt in Brazil started in the early 1990s, and at that time only three commercial products were available in the Brazilian market, all based on Btk (Dipel, Thuricide, and Bactospeine) (Habib and Andrade 1991). Approximately 40 commercial mycoinsecticides available in the Brazilian market are registered by 19 for-profit companies. More than 20 laboratories operated by sugar/ethanol mills produce *M. anisopliae* for their own use to control cercopids in cane fields (Kabaluk et al. 2010). Universities, research institutes, nonprofit organizations, rubber tree farms, and cattle farms also produce various fungal microbial control agents. By 2011, there were only 26 BCAs registered that is far less in comparison to 1,352 chemical pesticides (formulations and mixtures) registered. However, at the same time a number of unregistered BCA are also sold, and their number is higher in comparison to registered products, as the registration process involves high cost and length of time (Bettiol 2011). However, Argentina and Brazil have showed potential in utilizing biocontrol agents, and Cuba is also one of the leads in the pest management by biological means in Latin America (Sinclair and Martha 2001).

Africa

In Africa, biological control has been used for a long time to control invasive alien plant species (IAPs) (Olckers 1999). Besides this, devastating effects of locusts and grasshoppers on African agriculture had also realized the requirement of biological control (Groote et al. 2001). Application of fungal-based products of *M. anisopliae* has proven to be effective in pest management (Lomer and Prior 1992; Bateman 1997; Hunter et al. 2001). Studies of using viruses for control of insect pests are also reported, but their long-term effective commercial use is not well documented (Cherry 2004). In Africa, despite broad interest in the use of BCA, their availability to growers has until recently been very restricted because of limited demand, technical and financial constraints, and in-country regulatory frameworks (Cherry and Gwynn 2007). According to estimation, the annual biocontrol sales for the whole of Africa in 2003 were approximately $23 million, including $5 million for bacterial products (Guillon 2003). In Kenya, for example, in 2002, the total pesticide sales were valued at approximately $57.4 million, of which $1.15 million (2 %) are accounted for by BCA sales, predominantly Bt-based products (Wabule et al. 2004). Overall, the data are not very well documented for Africa.

Global Market

Biopesticide companies have invested billions of dollars to develop a variety of microbial products so as to eradicate crop diseases. It is impossible to starkly tell the market trends for biopesticides, and there is a considerable discrepancy in both predication of global sales and selecting category of biopesticides. Yet some reliable data sources are market survey websites and biopesticide companies. The biopesticide market is growing at more than 20 % per year, and there may be a tremendous increase possible in the next 5 years (Market and

Table 2.2 Worldwide biopesticide sales

	Estimated sales figures (in $US million)					
Biopesticide	North America	Europe	Asia and Australia	Latin America	Africa and Middle East	Total
Total Bt (products based on *B. thuringiensis* serotypes)	72.0	27.57	74.75	30.19	6.28	201.79
Other bacteria	23.94	6.30	14.05	4.56	0.40	49.25
Viruses	5.57	7.47	23.90	3.80	0.48	41.22
Fungi	15.85	5.64	18.85	35.96	0.78	77.08
Nematodes and other	9.4	7.50	0.95	0.16	0.13	18.14
Total	126.76	54.48	132.5	74.67	8.07	396.48

Source: CPL Business Consultants (2010)

Market 2013). In comparison, there is a gradual decline in synthetic, and the overall market for the biopesticides had increased from $672 million in 2005 to over $1 billion in 2010, at an annual average growth rate (AAGR) of 9.9 % (Industrial Equipment News 2013). A more detailed report by BCC Research (2012) expected biopesticides market to total $2.1 billion in 2012 which may exceed beyond $ 3.7 billion in 2017, with a compound annual growth rate (CAGR) of 12 %. An estimation of global biopesticide sales by CPL Business Consultants (2010) is given in Table 2.2.

Biopesticide Resources

In the field of biocontrol, modern technology and digitalization of print media offered quick access to several resources dealing with the matter of interest. There are myriads of literature available free of cost in the World Wide Web (www). Although this e-service has been very popular in developed countries, various databases and online services have been developed with the motive to benefit farmers and researchers so as to provide ampule amount of information indiscriminately. A summary of the databases and services are mentioned in Box 2.1.

Constraints with Biopesticides and Possible Remedies

Since biopesticide is a product generally with live organism(s), utmost care is needed, at all the steps, beginning from the production till the end use to maintain the microbial load and vigor. Production technology of biopesticide requires proper care and aid of sophisticated equipments to ensure availability of quality products in the market. As discussed again and again, biopesticides although offer a great promise are still not able to perform up to the mark, and in fact it will not be wrong to mention that these eco-friendly products have not taken market by storm and are performing below par. Kabi (1997) gave stress on the production of quality biopesticides, since they are important in rendering sustainability to farming systems. Insufficient knowledge, lack of adequate machinery, inappropriate handling and improper distribution, importation laws for live inoculants, and several other issues can lead to lack of quality products and loss of market. Major constraints associated with biopesticide development and growth are discussed in this section.

Lack of Awareness

Agriculture market is witnessing an increase in demand for environment friendly, chemical residue-free organic products. Growth in some regions is however hindered due to well-established chemical pesticide markets, lack of awareness about benefits of biopesticides, and uneven efficiency of biopesticides. The lack of awareness, knowledge, and confidence in farmers is one of the chief reasons for the lagging of these eco-friendly pest control alternatives. There are lots of ifs that farmers observe while using biopesticides; the results are sometimes not homogenous or consistent, and hence the users find themselves

Box 2.1: Biopesticide Resources

International Biocontrol Manufacturers Association (IBMA)

IBAMA is the worldwide association of biocontrol-based industries producing microorganisms, macroorganisms, semiochemicals, and natural pesticides for plant protection and public health. IBMA has 180 members and participates in the activities of international organizations such as OECD, FAO, WHO, the International Forum for Chemical Safety, the European Commission, etc. The main objective of IBMA is to associate the international organizations and manufacturers that are involved in the development and use of biocontrol agents. IBMA also maintains the product quality of the biocontrol agents and also forms and maintains the ethical professional rules. IBMA transfers the information for biocontrol agents to the interested parties and also organizes training program (details periodically updated at website: http://www.ibma.ch/news.html) to improve the skill of the company staff members for the better research. IBMA has four divisions; they are microbial biocontrol agents, natural and biochemical products, semiochemicals, and invertebrate biological control agents. IBMA provides a platform for the biocontrol products companies to share the knowledge and accordingly improve their business performance.

Online Information Service for Non-Chemical Pest Management in the Tropics (OISAT) was launched by the Pesticide Action Network (PAN) Germany in 2003, with the aim of limiting the use of hazardous pesticides and providing safer alternatives to poor farmers (Carina Webber 2008). OISAT info is a web-based information tool offering trainers, extension workers, and farmers a quick access to up-to-date information in the form of illustrations, photographs, and glossary terms in order to minimize pest damage in a safe, effective, and ecologically sound way. Every report or articles before publication undergoes a peer review by experts working on related fields then can be publically accessed at www.oisat.org

The International Organization for Biological Control (IOBC) was established in 1955 as a global organization affiliated to the International Council of Scientific Unions (ICSU). This nonprofit organization is known for its leadership in environmentally safe methods of pest and disease control and establishing a quality standard in the field of classical biological control (Cock et al. 2009).

Biopesticide Industry Alliance (BPIA) founded in 2000 with the mission of increasing awareness of biopesticide and to deliver full range of benefits of biopesticides in pest management program. BPIA is also involved in facilitating global acceptance, successful development, and commercialization of biopesticides. BPIA is a standards committee that evaluates and recommends quality and efficacy standards for biopesticides in agriculture, forestry, turf and ornamental, public health, consumer, and other target markets, even industry.

The Bio-Pesticides Database (BPDB) was developed by the Agriculture and Environment Research Unit (AERU) based at the University of Hertfordshire, the UK, is a comprehensive relational database of basic identification, physicochemical, toxicological, ecotoxicological, and other related data for both the more traditional agricultural pesticides (PPDB) and veterinary substances (VSDB). This database provides around 450 records of biocontrol agents ranging from naturally derived substances to insect predators (website http://sitem.herts.ac.uk/aeru/bpdb/index.html). BPDB retrieved information at global level from various resources such as scientific literature and databases, manuals, registration databases dossiers, company technical datasheets, and research projects. Before uploading data on the website, its quality is assessed that involves cross checking and peer review by experts.

confused in adopting these greener alternatives. Microbial pest control products require more attention of farmers than chemical products. Condition is worst in developing countries where most of the farmers are even not familiar with the term "biopesticide" and lack efficient skills to practice and use them (Alam 2000).

Research and development of biological pest control methods must be given priority, and people in general and agriculturists in particular must be educated about the handling and use of such control measures. It is absolutely necessary to create awareness, among the end users (farmers), regarding the use, efficacy, benefits, and importance of biopesticides, and also harmful effects of chemical pesticides must be known and explained. The responsiveness could be achieved by introducing certain extension activities such as organizing teaching programs, workshops, and entrepreneurs dealing with the idea of promoting sustainable agriculture using biological products (Amin 2013). Guidance, explanation, and monitoring should be done regularly by proceeding for interactive questionnaire sessions that will inculcate knowledge and learning in the farmers regarding the use, application, and handling of biopesticides. Farmers should also be trained for the methods of application in fields, and some encouraging activities can be introduced such as providing rewards to the farmers who applied biopesticides or promoted their use (Halim and Ali 1998). The efforts of various government agencies to popularize the use of biopesticides will definitely have impact in elevating current status and application of biopesticides all over the world. The National Farmer Policy (2007) in India has strongly recommended the promotion of biopesticides for increasing agricultural production and 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.

The use of transgenic crops like Bt crops is also not up to the mark especially in developing countries. In transgenic crops, functional foreign gene is incorporated by biotechnological tools. Objections to development and deployment of transgenic crops by farmers rest on several issues related to ethnic matters, associated risks, lack of confidence, costs, market control, etc. Farmers generally lack faith in the use of transgenic crop. Hence, it is essential that training and teaching should be given to the farmers in regard to the use of transgenic crops. Special schools should be established particularly in the rural areas so as to train and teach the farmers to efficiently use the biopesticides. Proper application of biopesticides is very important to achieve the optimum results. Farmers need to be made aware of the implications of chemicals on the current and future prospects of soil and yields. These goals can be achieved by the support of government and corporate houses.

Lack of Faith and Inconsistent Field Performance

Lack of faith in the use of biopesticides was found to be one of the major factors responsible for their lagging behind (Arora et al. 2010). Many farmers who stopped using biopesticides reported that it was mainly because the supply was extremely unreliable and the performance very inconsistent (Alam 2000). A key factor involved in the lack of success has been the rapid decline in the size of populations of active cells, to levels ineffective to achieve the objective, following introduction into soil. Abiotic soil factors (e.g., textural type, pH, temperature, and moisture) exert their (direct) effect on inoculant population dynamics by imposing stresses of various natures on the living cells introduced in the fields (Evans et al. 1993). They can also act indirectly by affecting the activity of the indigenous soil microflora. Hence, maintenance of sufficient activity of inoculated populations over a prolonged period after release often represents the main hurdle in the successful use of microbes as biopesticides (Arora et al. 2010). Furthermore, efficient introduction into soil during the growing season is a major technical constraint. It is extremely important that a minimum effective threshold population of the introduced biopesticide is maintained in the soil/rhizosphere so as to combat the pests and pathogens (Arora et al. 2010).

Building farmer's faith and confidence by developing appropriate stress-tolerating formulation can increase product stability, constancy, and viability that can reduce inconsistency in natural field conditions. Production technology, employed for designing biopesticides, should be improvised along with sophisticated quality control measures and monitoring facilities. The designed biopesticide should be reliable, specific, indigenous, and replicable in its activity. Extensive research should be conducted in the fields to develop appropriate formulation working efficiently under diverse in vivo conditions (Retchelderfer 1984; Greaves 1993). Technical and chemical compatibility along with innovative application methods is a prerequisite for the success of a new biopesticide product in the agricultural industry. Developed formulation should be compatible with crop production practices and equipment. The host range and abiotic conditions under which the formulation is most effective must be clearly mentioned on the packets and if possible explained to the farmers.

Poor Quality and Shelf Life

Poor quality and performance are also one of the serious problems that hindered biopesticides takeover on the market. Several workers reported that the biopesticides being sold in the market are contaminated and have a low count of microorganisms (Singleton et al.1996; Alam 2000; Arora et al. 2010). Due to low bacterial count, it is not surprising that their performance is poor, deprived, and uneven. Due to which the shelf life is low and inconsistent in performance resulting in decline in the demand.

The inconsistent and seasonal nature of the existing demand requires efficient storage. The storage of biopesticides requires special facilities and skills, which most producers, shopkeepers, and farmers do not possess. Shelf life is a cessation (end) of several factors like production technology, carrier and packaging material used, and mode and distance of transport. All these levels are desired to sustain the shelf life. Bacterial survival in the desired formulation is affected by several variables: the culture medium used for bacterial cultivation, the physiological state of the bacteria when harvested from the medium, the use of protective materials, the type of drying technology used, the presence or absence of contaminants, and the rate of dehydration (Paul et al. 1993). Extreme care should be taken throughout the designing process to minimize the chances of contamination. It is also important that precautions should be taken to avoid adulteration during packaging, storage, and application of biopesticides.

Future research efforts in formulation technology should emphasize processes that will achieve viable and stable biological products. The most suggested solutions to the problem of survival time are air-dried and lyophilized preparations of biopesticides (Nakkeeran et al. 2005). Decrease in the water content in the biopesticides can be used for long-term survival during storage. In this way, the bacteria in the formulation remain inactive, resistant to environmental stresses, insensitive to contamination, and thus become more compatible with chemical pesticide applications (Bashan 1998). However, dehydration phase is also the most sensitive part of the entire formulation process, especially for nonspore-forming bacteria (Shah-Smith and Burns 1997).

Hence, it could be suggested that the main factors that have potential to affect economic feasibility of the biopesticide product are designing and optimizing perfect formulation technology. Good formulation can be reflected by the long product storability. Several commonly used biopesticide formulations with extended shelf life include granules, pellets, and dry powder based. Granules can protect the active agent from desiccation and also provide basic food for the agent. Powder is easy to apply by suspending it in water and also can cover a wide area of application (Urquhart and Punja 1997; Amin 2013).

High Budget of Production and Lesser Agribusiness

Hi-tech instrumentation required for producing biopesticides under completely sterile conditions is not getting acceptance. Screening of suitable strains and research and development issues add to the budget. Large-scale screening of strains with biological activity is still required (comparable to more than 1:20,000 screened molecules for a new chemical product) (Bashan 1998). High sensitivity to temperature and other external conditions of these “living” inputs calls for enormous caution at the stage of manufacture/culture, transportation/distribution, and application. This involves investment in packaging, storage, and use of suitable carrier materials (Arora et al. 2001, 2010). In general, firms with larger production facilities are expected to invest more on networks to understand and access the market. All these factors prove that the raw material and instrumentation facility initially required for the biopesticide production are costly, and companies will only develop these products if there is a long-term profit in doing so. However, consistency and long-term returns can reduce the cost and enhance the profits.

A number of features of the agricultural economy make it difficult for companies to invest in developing new biopesticide products and, at the same time, make it hard for farmers to decide about adopting the new technology (Chandler et al. 2011). Most of the established companies relinquished their wish to do business in microbial pesticides but finally left the field due to huge losses in the agribusiness (CPL Business Consultants 2006). Commercial aspects of biopesticide industries were studied by various workers (Warrior 2000; Benuzzi 2004; Gelernter 2005) that confirm limited success and huge expenditure (Stewart 2001; Hallett 2005; CPL Business Consultants 2007; Droby et al. 2009). The market’s potential in business decision of biopesticide industry is now being forecasted by leading global management consulting and market research firms that suggest that the agribusiness dealing with biopesticides requires huge intake of money, high-risk factors, and less profit (Leng et al. 2011).

Henceforth, the profit in biopesticide business could be made only by using novel techniques and tools. Agribusiness companies need to use certain innovative techniques and cheap raw material to capture or protect market shares by offering new products that buyers want (product innovations) and also by cutting costs (process innovations) and minimizing risk factors. Multifaceted bioformulations based on microbial consortia with diverse activities can be useful in bringing down the costs. Biopesticides designed from consortia will have multiple and holistic applicability in promoting plant growth; protecting plant health; strengthening plant-microbe associations under stress, pollutant, or contaminant-affected regions; and protecting plants from the attack of phytopathogens through biological control (Arora et al. 2013). Advanced countries take advantage of technology, using a variety of procedures such as licensing, buying, and accessing what others develop (Pray and Nagarajan 2010, 2012). Product protection by patenting and support by government in taxation and infrastructure development can also help.

Regulatory Framework

Registration of biopesticide is the main hurdle in the development, and most of the times registration is much more expensive than the production. Registration is not only expensive but also time-consuming (Ehlers 2006). The main problem is that biopesticides contain active cells (live organisms), and these live forms are treated like pathogens by the government agencies. Another issue is regarding the import and export of biopesticides; again, it should be pointed that export and import of chemical pesticide is much easier (as no one doubts on its integrity) in comparison to the use of biopesticides.

The assessment of risks is important because it provides the basis for governments’ decisions whether to approve or register new biological pesticides and whether to renew the registration of old ones. Registration requires collation of data and preparation of dossier for submission to a national regulatory authority. By these efforts, governments can speed up the process of approving safer new pesticides and stopping use of riskier ones. Some major countries and their registration details are provided in Table 2.3. USEPA encourages development and use of

Table 2.3 Biopesticide regulation structures in different countries

Name of country/ continent	Registration/governing bodies
The USA	The USEPA is the main authority to regulate the use, sale, and distribution of conventional chemical and biological pesticides. USEPAs do this primarily from three statutes: (1) the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) as amended, (2) the Federal Food, Drug, and Cosmetic Act (FFDCA), and (3) the Food Quality Protection Act (FQPA) of 1996. All ensure that pesticides use does not cause unreasonable adverse effects to humans or the environment
Europe	Here, the term "biopesticide" generally includes products with active substances based on microorganisms, botanicals (or biochemicals or plant extracts), and semiochemicals (including pheromones) and regulated under the Council Directive 91/414/EEC. This directive provides a list of active substances authorized for incorporation in plant protection products and lays down the requirements for application dossiers for new active substances and new plant protection products
China	In 1997, The Regulation on Pesticide Administration was introduced (revised in 2001 and 2004) to supervise and control manufacturing, marketing, and use of pesticides/biopesticide and agrochemicals in China or import to China
Australia	Registration of pesticides is governed by the Agricultural and Veterinary Chemicals Code Act 1994 and administered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). The importation of a biological agent also requires authorization from the Australian Quarantine Inspection Service (AQIS) prior to introduction. If the organism has been genetically altered, approval from the Office of the Gene Technology Regulator (OGTR) is required prior to importation or release
India	Biopesticides fall under the Insecticide Act (1968). Central Insecticides Board (CIB) and the Registration Committee (RC) are two "high-powered" bodies under this Act. CIB is the Apex Advisory. It comprises eminent scientists of all disciplines/fields concerned. Whereas, the RC grants registrations to the persons desiring to import or manufacture insecticides, after scrutinizing their formulae and verifying claims with respect to their bio-efficacy and safety to human beings and animals
South Korea	Registration at first level is governed by the Agromaterials Management Division (AMD) and the Rural Development Administration (RDA), and then a new record is evaluated by Pesticide Safety Evaluation Division (PSED) and National Academy of Agricultural Science (NAAS). Once this dossier is deemed to contain sufficient information, the PSED holds two technical expert committees for product management and safety management. The committees provide the examination results to the PSED, who adjust the results and reports to the AMD and RDA. The AMD have a dedicated council for agrochemical safety for the final decision and for reporting to the applicant's dossier

Source: Kabaluk et al. (2010)

biopesticides. Since biopesticides tend to pose fewer risks than chemical pesticides, EPA generally requires much less data to register a biopesticide than to register a conventional pesticide (Kumar 2012).

The governments can frame regulations at the global level by organizing meetings, workshops, and conferences regarding uplifting the status of biopesticides/bioformulation. Governments should set up regulatory framework that could be accepted globally. Presently, different countries have different rules, and regulations due to which problems related to registration, use, import, and export do occur. The regulation can set up uniform acts or laws that could be accepted globally, so that there is a common policy regarding the use of biopesticides.

Health and Ecological Risks

There may be some chances of adverse health effects if biopesticides are not used according to the instructions mentioned on the product, but in comparison to chemical pesticides, risks are far lower. Biopesticides containing Bt as active ingredient are not reported to show any major adverse effects on human health, but in some cases, occupational exposure confirmed health risks (Green et al. 1990; Bernstein et al. 1999; Doekes et al. 2004). Studies on fungal biopesticides suggest that spore of entomopathogenic fungi such as *Trichoderma*, *M. anisopliae*, and *B. bassiana* may cause allergy to farmworkers (Iida et al. 1994; Darbro and Thomas 2009). Recently, studies on mice confirmed as a robust fungal allergen from biopesticides of *M. anisopliae* (Ward et al. 2009, 2011). *M. anisopliae* is also reported to affect survival of nontarget pests (Thungrabeab et al. 2006).

Thus, it is necessary that before developing a biopesticide, strain monitoring should be extensively done. Doubtful strains should be screened out, as adding such microbes may result in the loss of confidence. However, care must be undertaken to ensure that any newly introduced natural product, being a microbial agent or secondary metabolite, should possess no threat to the operator, the environment, or the consumer before it is introduced into crop protection systems (Copping and Menn 2000). Apart from it, governments should also set up defined standards and permissible limits in regard to using biopesticides so that it diminishes the health risks. Essential data regarding the composition, toxicity, degradation, and other characteristics of the biopesticides is important and should be submitted to the respective agencies of various countries. In the USA, the registrants have to submit to EPA so as to ensure that the pesticide is safe for use. EPA conducts rigorous reviews to ensure that pesticides do not have adverse effects on human health or the environment (Kumar 2012).

Problems Associated with Viral Biopesticides

The main problem associated with viral biopesticides is the requirement of live host, tissue, or cell line culture for the proliferation and cultivation. Development of tissue culture laboratory in an institute (that works on viruses) again needs ethical clearances from the government organizations (Lapointe et al. 2012). The main cons of viral biopesticides are the culturing techniques, handling errors, and upsurge costs that ultimately hamper growth, production, and manufacture.

In all viral pathogens, including the most common biopesticides, the baculoviruses, replication is dependent upon the availability of permissive host cells. The accessibility and susceptibility of host cells to viral invasion and replication are classified into three categories: permissive, semi-permissive, and nonpermissive. In semi-permissive, infections result in limited viral progeny resulting from defects in some replication events, such as gene expression or viral DNA replication. In nonpermissive infections, cells do not support viral replication, and the process does not yield infectious progeny (Lapointe et al. 2012). Determining what factors influence the level of permissiveness of an insect cell to a particular baculovirus has proven to be challenging because baculovirus host range is affected not only by the interactions between the baculovirus and the host cell at the molecular level but also by aspects of insect behavior and physiology (Miller and Lu 1997; Cory and Hoover 2006; Thiem and Cheng 2009). Research and innovative techniques are required so as to ease the production, reduce the cost, and simplify the application of viral pesticides.

Competition with Chemical Pesticides

All over the world, chemical pesticides are used in very high amounts (Donaldson et al. 1995), and one-third of the agricultural production is dependent on pesticides (Liu et al. 2002). According to USEPA, over 1 billion tons of pesticides are used in the USA every year, and this is 22 % of the estimated 5.2 billion pounds of pesticides used worldwide (USEPA 2011). Consumption of pesticides in some of the developed countries is almost 3,000 g ha^{-1} (Khater 2012). Practically, biopesticides are not as effective as chemicals. Ahmad et al. (2007) compared the effectiveness of *B. thuringiensis* with, megamos (chemical pesticide) in controlling thrips

(*Thrips tabaci*) on garlic (*Allium sativum*) and found maximum yield using megamos treatment. In case of chemical pesticides, lesser quantity is suffice to kill a vast quantity of pests which is the main reason why farmers choose chemical pesticides over biopesticides. There have been several cases where chemical pesticides reduced losses of many crops, and in their absence it is reported that global losses would have risen from present levels of around 42 % to close to 70 % (Oerke et al. 1994). Knuston et al. (1990) provided further detail that in the absence of chemical control of weeds in wheat production, US yields would fall by 30 % and 5 % in the absence of fungicides and herbicides (Knutson et al. 1990). Similar studies also confirmed chemical dependence for the production of major crops around the globe (Farah 1994; Warren 1998; Webster et al. 1999; Aktar et al. 2009). Some workers are working on synergistic action of microbial biopesticides and chemical pesticides by IPM programs (Irigaray et al. 2003; Koppenhöfer and Fuzy 2003). IPM can also result in gradual decrease in the use of chemicals leading to development of confidence among farmers for the biopesticides. Research on combining microbial biopesticides with synthetic pesticides has showed improvement in control of some pest species including pesticide-resistant varieties (Khalique and Ahmed 2001; Cuthbertson et al. 2005). By removing the previously mentioned hurdles and constraints, confidence for biopesticides can be developed. This will only enhance the market for them. Quality products with the ability to act in field conditions will be able to compete with the chemicals and gradually overtake the market.

Conclusion

Since inception of biopesticides, their position and situation still remains in dilemma. Farmers find themselves confused and less confident in selecting biopesticides over the synthetics. Despite the fact that presently biopesticides are being used everywhere in the world, it is also known that developed countries seem to be ahead in their wider application (Chandler 2011). Developing countries have huge possibilities for using biopesticides as the production can be less expansive and labor is cheap in comparison to developed nations (Roettger and Reinhold 2003). Also countries like India are vastly dependent upon agriculture for not only feeding their populations but also for the economy which depends majorly on this sector. However, most of the challenges faced for the upliftment of biopesticides are fundamental and cosmopolitan. These include the efficacy of the microbial activity, survival of microorganisms, delivery systems, determining host range, and avoiding injury to nontarget organisms, consistency, performance in field conditions, economics, government regulations, and confidence among the end users. Gelernter (2007) has described the future of biocontrol in Asia, and according to him unreasonable expectations for performance, inappropriate regulatory guidelines, lack of documentation on the uptake of microbial control strategies, difficulties in implementing local production schemes, and inhibition of scientific exchange are the main hurdles in establishment of biocontrol. Biopesticide production also faces problem of quality control, and at the global level there is no uniformity in processes and methods. In this regard, Van Lantern (2003) starkly emphasized that the characteristics that affect overall quality have to be identified and must be quantifiable and relevant for the field performance of the parasitoid or predator. Though a lot of research is going on biopesticide development, but still it is further needed to be emphasized and explored (Gaind and Kaushik 2008). This exploration could be done by developing strong policy and encouragement from governments to the industry as well as end user by means of liberal tax benefits, incentives, etc. Creating awareness among the farmer community about the beneficial effects of BCAs and harmful effects of chemical protectants will certainly create a congenial and long-standing effect which can lead to commercial success of the biopesticides (Swati and Adholeya 2008).

In spite of all these limitations, biopesticides are gradually becoming popular, especially among local farmers, and that is why a statement of David Cary, executive director of the IBMA, provides a hope of betterment that the biological control market "that is only 3 %, or $1.3 billion, of the $44 billion global crop protection business, is growing 10 % a year" (Patrick and Kaskey 2012). The growth of biopesticides is indicative of its importance in the sustainable agriculture by producing food crop with lesser chemical use. There is prediction that the world population will exceed nine billion by 2050, and efforts have to be made to meet the demand of 70–100 % more food from the same land area without the extensive use of chemicals (http://unsdsn.org/files/2013/05/130112-HLP-TG7-Solutions-for-sustainable-food production.pdf). Currently, the ultimate requirement for biopesticides to develop is to overcome the shortcomings which are associated with them. This reformation will certainly create similar acceptance as the synthetic pesticides and importantly without any adverse effect on the environment. A concerted effort of research institutes, universities, nongovernment organizations (NGO), and government organizations is required to elevate the stature of biopesticides. Determination at global level is required to strengthen these green alternatives and push off the red poisonous chemicals from our platter and of course the ecosystem as a whole.

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