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Biofertilizers and Biopesticides: A Holistic Approach for Sustainable Agriculture

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CONTENTS

ABSTRACT Among the major environmental concerns in the world today, contamination of mother's breast milk through the excessive and injudicious use of agrochemicals is a grave threat to humankind. It has occurred due to the paradigm shift in agricultural practices from conventional natural products to anthropogenic chemicals as fertilizers to sustain the food demand of a rising human population. Though chemical pesticides could contribute substantially to modern agricultural production systems, they alter the ecological balance and an unintended effect of that is irrevocable harm to humans and other species. Ensuring environmentally sound and sustainable crop production without causing detrimental effects to biodiversity, therefore, is the most significant challenge for humankind in this century. The potential of biopesticides and biofertilizers in promoting sustainable agriculture has been evidenced in recent years. The demand for organic farming products is expected to escalate globally in the near future, as they are a cost-efficient and renewable source for sustainable agriculture. Integrated pest management (IPM) and integrated nutrient management (INM) are two key driving forces for biopesticides and biofertilizers. This chapter deals with the harmful effects of chemical fertilizers to the

environment as well as the scope and benefits of biopesticides and biofertilizers to attain food security for the growing population through enhanced quality and restoration of soil fertility for sustainable development.

9.1 Introduction

As per a United Nations (UN) report, global population is projected to stabilize at around 9.2 billion by the year 2050 and the global agricultural production rate is projected to be doubled to meet the increasing demands (Ray et al., 2013). On the contrary, the primary natural resources needed for agricultural productivity, such as land, water, and biodiversity, are deteriorating both qualitatively and quantitatively at an alarming rate. For instance, regarding water availability, 30% of crop production will be at severe risk by the year 2025 (Pimentel et al., 2004). Moreover, as per World Bank projections for the year 2050, climate change could dampen crop yields by 20% or more (Alexandratos and Bruinsma, 2012). Therefore, the critical situation is that we have to ensure huge crop production to meet the ever rising demand for finite natural and nonrenewable resources. Since agriculture is both the victim and contributor to greenhouse gas (GHG) emissions, a two-pronged approach is needed to develop adaptive measures that will enhance agricultural resilience (Tuteja and Singh, 2012).

9.1.1 Importance of Soil Nutrients for Agricultural Biodiversity

Several nutritious elements are required for proper plant growth, which directly impacts agricultural biodiversity. Only a minor portion of the nutrients from the soil reserves is released each year through biological activity and/or chemical processes, and most agricultural lands are deprived of some essential nutrient or the other (Feller et al., 2012). In specific, 17 plant food nutrients are essential for proper crop development as shown in Figure 9.1. Although all the nutrients are equally important to plant growth, each of them is required in vastly different amounts. Based on this property, the essential elements needed for the plant growth could be categorized into three classes—primary (macro) nutrients, secondary nutrients, and micronutrients.

Nitrogen, phosphorus, and potassium, which are required in high quantities, are the primary macronutrients. They are frequently supplied to plants in the form of fertilizers. Nitrogen is needed in huge amounts for the growth of plants, since it is the basic constituent of proteins and nucleic acids. Phosphorus is one of the essential primary elements for plant nutrition that plays a significant role in several processes of plant cell growth such as photosynthesis, respiration, energy storage and transfer, cell division, and enlargement. Phosphorous could be assimilated by plants only as soluble phosphates. Moreover, most of the phosphatic soil content in nature exists in the form of rock phosphate and organic phosphorus, both of which are poorly soluble in water. The ability to revitalize the phosphorus content in the soil is solely dependent on the complex chemistry of the soil system. An inadequate availability of phosphorous to the crops could reduce the seed size, seed number, and viability. Potassium is another vital component needed for effective functioning of nutrient absorption, respiration, transpiration, and enzyme activity. However, potassium remains in ionic form and does not become part of plant compounds.

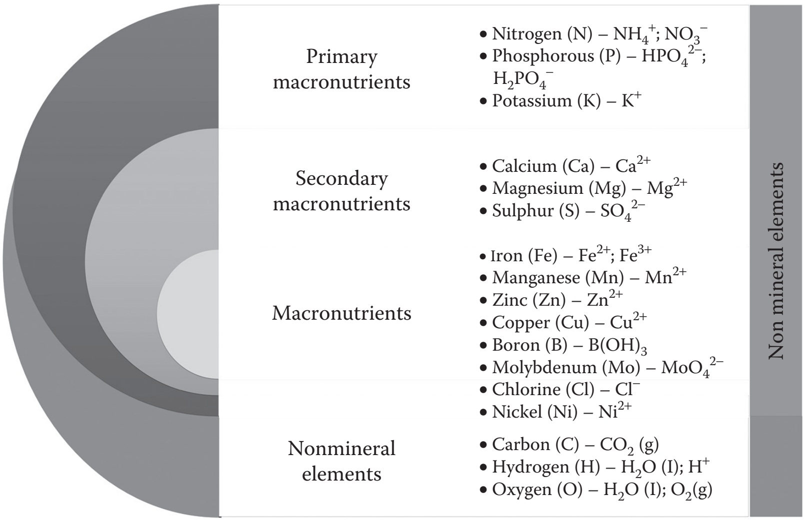

FIGURE 9.1
List of essential plant nutrient elements and their primary forms of availability.

The second class of nutrients such as sulfur, calcium, and magnesium are needed in slightly lesser amounts than primary nutrients for most crops. Often, the secondary nutrients are readily available and in adequate supply. However, these secondary nutrients are gaining significant attention in case of crop fertilization programs to overcome the shortcomings of unavailability as that could limit the overall plant growth even if all other primary nutrients are available unlimitedly in the soil. Micronutrients are elements required in very meager amounts for the overall development of plants and the cost-effective crop production. For instance, micronutrients such as boron, chlorine, copper, iron, manganese, molybdenum, and zinc act as activators and are responsible for the regulation of many functions in plants.

9.1.2 Problems with Existing Agricultural Systems

The land is a natural resource for human beings and a habitat for many living organisms. Population explosion over the past few centuries has raised the demand for greater agricultural productivity. The unprecedented increase in diversion of agricultural lands to nonagricultural purposes has mounted up the deficiency of arable lands. There has been a decrease in agriculture productivity due to several reasons such as increased soil nutrient deficiency, massive build-up of obnoxious weeds and pests, escalated production cost, and so on. As an outcome, the growth rate of agricultural productivity could not sustain the population growth rate. This situation mounted pressure on several developing countries and has led to the usage of chemical fertilizer and pesticides over natural fertilizers to increase productivity because of availability and affordability (Zendejas et al., 2015). Specifically, agriculture suffers from both constructive and harmful effects of the usage of chemical fertilizers and pesticides on the soil. Although a wide array of chemical pesticides have been applied to overcome the economic losses in agriculture, they have caused several environmental stresses on nontarget organisms present in the soil (Zahran, 1999). The use of chemical fertilizers and pesticides has resulted in land degradation and loss of soil fertility (Liu et al., 2009). Apart from being hazardous to the balance in the soil ecosystem, they cause adverse effects on human beings and the environment. Chemical pesticides such as atrazine, 2,4-dichlorophenoxyacetic acid, leave a sustained residue in food products like fruits and vegetables and are considered to be serious public health concern. Magner et al. (2015) investigated a pilot study of human exposure to pesticides from food and found higher concentrations of chemical residues in the urine samples of children. Lu et al. (2015) studied the impact of soil and water pollution on food safety and health risks in China and emphasized that a holistic approach is needed to tackle the problems of environmental pollution and food safety.

Another important problem caused by the usage of chemical fertilizer is contamination of groundwater and surface water along with nutrient imbalance of soil. For instance, inefficient uptake of nitrogen fertilizers by plants contributes to nitrate contamination of soils and groundwater, leading to health hazards and compromising agricultural sustainability (Santi et al., 2013). The primary nutrients present naturally in the soil are depleted due to the residual accumulation of chemical pesticides and fertilizers (Savci, 2012). Chemical fertilizers are highly resistant to degradation and therefore reduce soil fertility and decrease nitrogen fixation either through alteration of root nodules or reduction of the nodulation by soil bacteria. Further, the crops also develop resistance to the pesticide absorption (Zahran, 1999). In subsistence agricultural systems, crop yields are directly dependent on the inherent soil fertility and microbial processes that govern the mineralization and mobilization of nutrients required for plant growth (Choudhary et al., 2011). Since productivity is often limited by the availability of soil nutrients and relies on the interface of the rhizosphere between living roots and soils, any shift in the microbial community structure could lead to significant changes in agroecosystems. The benefits and drawbacks of using chemical fertilizers in agricultural activities are shown in Figure 9.2.

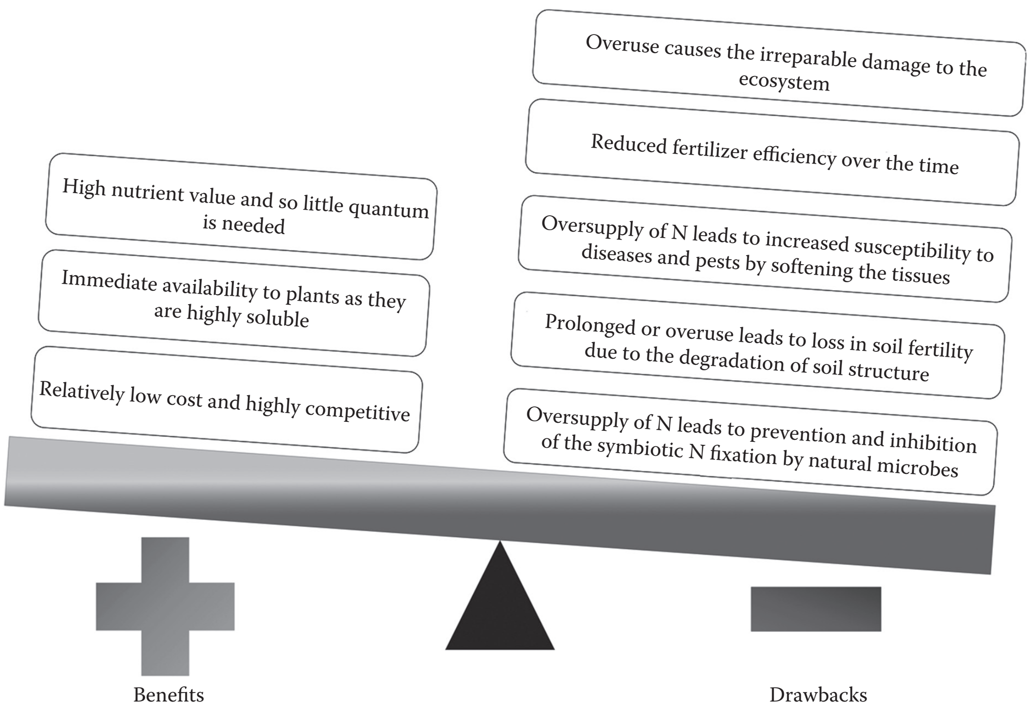

FIGURE 9.2
Benefits and drawbacks of using chemical fertilizers in agriculture.

There has been a growing concern in recent years about the excessive usage of chemical pesticides and its impact on nature and natural resources including humans (Pimentel, 1996; Margni et al., 2002). Over the years, the mounting evidence of the adverse effects of chemical pesticides has contributed to changing the conception of "pesticide as panacea." Further, it has strengthened the advocacy of biopesticides and led to intensive biopesticide research programs in various institutions across the world (Rossel et al., 2008). Moreover, particularly in the last three decades, this shift has resulted in an avalanche of reporting in scientific literature attempting to discover and develop newer and safer pesticides (Koul and Dhaliwal, 2001, 2002; Sinha, 2012).

The challenge of attaining sustainability that is inclusive of economic growth and food security has added another dimension due to the problems posed by climate change. The ever increasing emissions of GHGs have led to several environmental menaces like global warming, rise in sea level, disturbed rainfall pattern with frequent droughts and floods, and so on. These extreme environmental changes hinder the overall plant growth. For instance, in the recent decades, the yield of economically important crops has been drastically declining due to several abiotic stresses. Therefore, adverse impact of climate change on economic stability and overall agricultural productivity is causing increased vulnerability of resource-poor farmers (Tuteja and Singh, 2012). However, plants are subjected to overcome the environmental stresses through the development of tolerance, resistance, or avoidance mechanisms by adjusting to a gradual change in its environment that allow the plants to maintain performance across wide range of environmental conditions (Mohammad et al., 2007).

9.1.3 Need of Biofertilizers and Biopesticides for Sustainable Agriculture

Today's agricultural productivity is influenced by several biotic and abiotic factors such as high salinity, extreme temperature, and droughts and floods due to seasonal variations. Other biotic factors such as weeds and pests also significantly influence the qualitative and quantitative production of agricultural products. As stated above, the indiscriminate use of chemical fertilizers and pesticides has generated several environmental problems along with ill-effects of long-term health impacts on animals and humans. Some of these issues could be tackled effectively by promoting ecologically based management of nutrients and pests by the use of biofertilizers and biopesticides. Because they are natural, they ensure supply of essential nutrients, maintain soil structure, and establish a balance of ecosystems. The appropriate utilization of biofertilizers and biopesticides holds the sustainable approach to enhance agricultural productivity. Several countries such as Argentina, Australia, Brazil, Canada, India, the Philippines, South Africa, and the Unites States, among others have practiced these technologies for promoting sustainable agriculture. For instance, most of the nitrogen demand by the crops to date is supplied in the form of synthetic chemical fertilizers such as urea. Such chemical fertilizers impose a health hazard to agroecosystems and humans besides being quite expensive, leading to increase in the production cost (Tiwary et al., 1998). Encouraging the alternative means of soil fertilization solely relies on the natural/organic inputs to improve the nutrient supply and conserve the ecosystems (Araujo et al., 2008). The appropriate utilization of biofertilizers paves the way for the enrichment of micro- and macronutrients through fixation of nitrogen, solubilization or mineralization of phosphate and potassium, the release of plant growth–regulating substances, production of antibiotics, and biodegradation of organic matter in the soil (Sinha et al., 2014). Overall, it improves plant productivity by enhancing the soil fertility and promoting the soil ecosystem. Precisely, the narrow zone of soil surrounding plant roots named rhizosphere could comprise up to 10^{11} microbial cells per gram of root and above 30,000 prokaryotic species (Mendes et al., 2013; Bhardwaj et al., 2014).

It has been revealed that the effect of nitrogen fixation induced by nitrogen fixers is not only significant for legumes but also for nonlegumes. The symbiotic association of rhizosphere with nitrogen-fixing microbes and plants is a major driving force for the flourishment of the biosphere and adaption to a variety of environmental stresses (Santi et al., 2013). Therefore, the utilization of both chemical fertilizers and biofertilizers has its benefits and drawbacks in the context of nutrient supply, crop growth, soil fertility, and other overall environmental qualities (Chen, 2006). Therefore, the rewards need to be integrated and appropriate use of biofertilizers should be taken up to achieve balanced nutrient management for a dynamic crop growth. The benefits and drawbacks of using biological fertilizers in agricultural activities are shown in Figure 9.3.

Biological regulation is the process of maintaining particular microbial population at its desirable limit, beyond which it could act as a pest. To subdue pest densities while conserving and augmenting native agents, other living organisms are introduced to the environment by the process called importation. This is one of the three major ways to implement biological regulation. The other two processes are conservation/augmentation of natural enemies (disease-causing agents, predators, parasitoids) and application of microbial pesticides (Szewczyk et al., 2006).

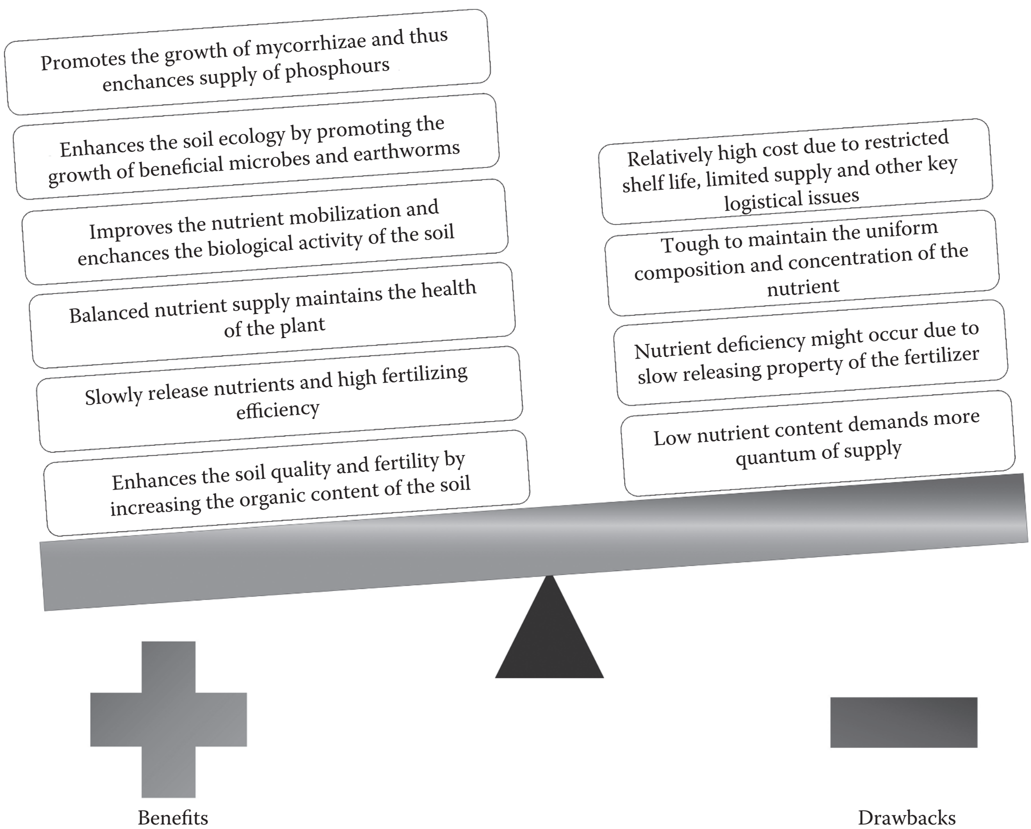

FIGURE 9.3
Benefits and drawbacks of using biofertilizers in agriculture.

9.2 Biofertilizers

Biofertilizers are defined as biologically effective products and/or microbe-based inoculants of bacteria, algae, and fungi either as individual agents or in combination that may help in biological nitrogen fixation or any other beneficial activity for the plants. It also includes organic fertilizers such as manures and other related products for the associated interaction of microbes with plants. Biofertilizers offer several beneficial functions to the plants such as nitrogen fixation, solubilizing, and stabilizing of phosphate in addition to aiding in the supply of other essential micronutrients (Bhardwaj et al., 2014). Based on the functions of biofertilizers, it could be classified into various categories, and the most significant ones are those that establish a symbiotic relationship where both the partners derive benefits from each other.

9.2.1 Types of Biofertilizers

Biofertilizers could be broadly classified as symbiotic nitrogen fixers (*Rhizobium* sp. for legumes); asymbiotic free nitrogen fixers (*Azotobacter*, *Azospirillum*, etc.); cyanobacteria (*Aulosria*, *Nostoc*, *Anabaena*, etc.); and algal biofertilizers (blue green algae in close association with/without Azolla) for wetland rice phosphate-solubilizing bacteria (PSB), mycorrhizae, organic fertilizers, and *Azotobacter/Azospirillum* (Zahran, 1999; Shridhar, 2012). This broad array of biofertilizers could act upon several crops and play a significant role in sustainable agriculture. Microbial species belonging to PSB are *Pseudomonas*, *Bacillus*, *Rhizobium*, *Agrobacterium*, *Burkholderia*, *Achromobacter*, *Micrococcus*, *Aerobacter*, *Enterobacter*, and *Flavobacterium*. These PSBs secrete organic acids and lower the pH to dissolute the bound phosphates present in the soil. The phosphatic biofertilizers such as the bacterial species including *Thiobacillus*, *Bacillus*, and others, along with the mycorrhizal fungus *Glomus* sp. help in increasing the solubility or availability of nutrient phosphate from its existing sparingly soluble forms. However, these microbes do not bring in phosphorus from outside, rather they deplete the soil phosphate reserves. While considering the low utilization efficiency of chemical phosphatic fertilizers, phosphate-solubilizing biofertilizers could play a significant role in improving the efficiency of utilization of phosphate residues left in the soil.

It is beyond the scope and context of this chapter to outline a complete and exhaustive literature survey of the list of microbes that could be utilized as biofertilizers. However, an attempt has been made to summarize the available literature briefly with special emphasis on the classifications of biofertilizers based on the existing literatures of nature and origin to convince the readers. Table 9.1 lists the various types of fertilizers with limited examples.

9.2.2 Mode of Action of Biofertilizers in the Soil

The appropriate use of biofertilizers aids in fixing the atmospheric nitrogen in the soil and root nodules of the legume crops and enhances the overall bioavailability of the nutrients to the plants without adversely affecting the soil and environment. Further, they scavenge the phosphate from soil layers and solubilize the insoluble forms of phosphates into available forms. Many times, the biofertilizers produce hormones for promoting the growth of root nodules and assists in soil mineralization through effective decomposition of the organic matter. Hence, the mode of operation of biofertilizers in the soil varies with the desired applications.

TABLE 9.1

Types of Biofertilizers with Examples

Categories	Subcategories	Examples
Nitrogen fixers	Free living	*Azotobacter: A. chroococcum, A. vinelandii, A. beijerinckii, A. insignis, A. macrocytogenes; Beijerinckia, Clostridium, Klebsiella, Anabaena, Nostoc, Trichodesmium*
	Symbiotic	*Rhizobium, Bradyrhizobium, Sinorhizobium, Azorhizobium, Mesorhizobium, Allorhizobium, Frankia, Anabaena azollae*
	Associative symbiotic	Azoarcus sp., Alcaligenes, Acetobacter diazotrophicus, *Azospirillium: A. amazonense, A. halopraeferens, A. brasilense, A. lipoferum, Alcaligenes, Bacillus, Enterobacter, Herbaspirillum, Klebsiella, Pseudomonas, and Rhizobium*
Phosphate solubilizers	Bacteria	*Arthrobacter* sp., *Bacillus* sp., *B. atrophaeus, B. circulans, B. licheniformis, B. amyloliquefaciens, B. firmus, B. megaterium, B. polymyxa, B. subtilis, Chryseomonas luteola, Enterobacter aerogenes, E. asburiae, E. taylorae, E. intermedium, Kluyvera cryocrescens, Micrococcus* sp., *Penibacillus macerans, Pseudomonas aerogenes, P. cepacia, P. straita, Vibrio proteolyticus, Xanthobacter agilis*
	Fungi and actinomycetes	*Aspergillus* sp., *A. amstelodemi, A. awamori, A. candidus, A. foetidus, A. fumigatus, A. aponicas, A. niger, A. tamari, A. terricola, A. flavus, Chaetomium nigricoler, Penicillium* sp., *P. digitatum, P. simplicissimum, P. bilaji, P. canescens, P. radicum, P. rugulosum, P. variable, Scwaniomyces occidentalis, Streptomyces* sp.
Phosphate stabilizers		*Pseudomonas, Bacillus, Rhizobium, Burkholderia, Achromobacter, Agrobacterium, Microccocus, Aereobacter, Flavobacterium and Erwinia, Pseudomonas putida, Pantoea agglomerans*
Phosphate stabilizers by mycorrhiza	Arbuscular mycorrhiza	*Acaulospora* sp., *Gigaspora* sp., *Glomus* sp., *Scutellospora* sp., *Sclerocystis* sp.
	Ectomycorrhiza	*Laccaria* sp., *Pisolithus* sp., *Boletus* sp., *Amanita* sp.
	Ericoid mycorrhizae	*Pezizella ericae*
	Orchid mycorrhiza	*Rhizoctonia solani*
Potassium solubilizers		*Bacillus mucilaginous*
Plant hormones producing bacteria	Gibberellins	*Bacillus pumilus* and *B. licheniformis,*
	Cytokinins	*Paenibacillus polymyxa*
Plant growth–promoting rhizobacteria		*Achromobacter, Pseudomonas fluorescens*
Biofertilizers for micronutrients	Zinc solubilizers	*Bacillus* sp., *B. subtilis, B erythropolis, B. pumilus, P. rubiacearum, Thiobacillus thioxidans*, and *Saccharomyces* sp.
	Silicate solubilizers	*Bacillus* sp.

Biofertilizers are mainly prepared in a liquid medium, and there are several ways of applying them to the crops. Three ways of using liquid biofertilizers are seed treatment, root dipping, and soil application. Seed treatment is the most commonly used method due to its high effectiveness and relatively low cost. In this method, the seedlings are soaked in the biofertilizer solution followed by their transplantation. In the case of root dipping, roots are dipped in the synthesized biofertilizer solution before transplantation. This method is quite useful for most of the vegetables and crops. Soil application is carried out during the preparatory phase and leveling of the soil before seeding.

The various methods of application of biofertilizers have been summarized in Table 9.2. Bacteria belonging to different genera including *Achromobacter*, *Azospirillum*,

TABLE 9.2

Method of Application of Biofertilizers and Its Suitable Crops

Method of Application	Efficacy in Crops	References
Soil treatment: Soil is mixed with biofertilizers before planting or sowing. One part of biofertilizers is to be added for four parts of carrier	Maize and wheat	Schoebitz et al. 2014
Seed treatment: One part of biofertilizers is to be added for 50 part of seeds in the prepared slurry (water to be added in the ratio of 1:2)	Pulses, oilseeds, and fodder crops	Singh et al. 2013b
Seedling treatment: Seedlings are dipped in solution (one part of biofertilizers is to be added for 10 part of water) for 40 minutes	Paddy, tomatoes, potato, onion, marigold, and jasmine	Andrade et al. 2013
Set treatment: Sets are immersed in the biofertilizers solution for 30 minutes	Sugarcane, banana, and grapes	Shen et al. 2013
Fertigation: Biofertilizers are added in water with required micronutrients	Orchard crops like mango, lemon, custard apple, vine, and peaches	Singh et al. 2013a

Bacillus, *Burkholderia*, *Enterobacter*, *Microbacterium*, *Methylobacterium*, *Pseudomonas*, *Pantoea*, *Paenibacillus*, *Rhizobium*, and *Variovorax* provide tolerance to host plants under different abiotic stress environments (Egamberdieva and Kucharova, 2009). Free-living nitrogen-fixing bacteria such as *Azotobacter chroococcum* and *Azospirillum lipoferum* have been found to have the ability to release phytohormones similar to gibberellic acid (GA) and indoleacetic acid (IAA) that could stimulate plant growth, absorption of nutrients, and photosynthesis in addition to fixing nitrogen (Fayez et al., 1985; Mahfouz and Sharaf-Eldin, 2007).

9.3 Biopesticides

Biopesticides are pesticides derived from either animals, plants, or microorganisms such as bacteria and viruses. These biobased control agents are advantageous because of their inherently less harmful nature in comparison to chemical pesticides and are thus considered to be ecofriendly and safe. Further, these biopesticides are more target-specific than chemical pesticides, that is, they affect only the target pests and their close relatives. On the contrary, chemical pesticides often destroy beneficial insects as well and thereby harm the ecosystem. Due to their high target specificity and nonpersistent and rapid decomposition nature, the development of resistance in the particular pest is also reduced to a great extent. The frequency and quantum of biopesticides required on the farm are relatively small. Moreover, the yield and quality are enriched along with better social acceptability. They are also highly suited for economically deprived rural areas. This has led to an upsurge in economic benefits of these farm products because of the enhancement of product quality and, thereby, increase in export businesses and related activities.

Biopesticides have been accepted globally, of late, and the net market witnessed the remarkable growth rate of 10%–15% per annum (Wahab, 2009). To date, biopesticides share a small pie of global pesticide market, yet the growth of biopesticides is faster due to rising demand for organic agricultural products from Western countries (Hassan and Ayhan, 2014). Though hundreds of naturally occurring insect-specific (entomopathogenic) bacteria have been isolated from insects, plants, and the soil, very few have been studied intensively. Much attention has been given to *Bacillus thuringiensis* (*Bt*), the most promising biological control agent for pest and insect management, as many of its strains are toxic to particular groups of insects. As an outcome, *Bt* has been commercialized and sold under various trade names over the past several decades. A wide array of these natural bacteria isolated from the soil and plants could produce a crystal protein, which is toxic to broad groups of insects.

9.3.1 Types of Biopesticides

Biopesticides can be categorized into three types: microbial pesticides, biochemical pesticides, and plant-incorporated protectants. Besides these, biopesticides also include entomopathogenic nematodes, parasites and predators, plant extracts and secondary metabolites, and so on. Biopesticides may also be classified according to the target organism: bioinsecticides, bioherbicides, and biofungicides. Approximately 75% of biopesticides used currently consists of *Bt*-based products. The live microbe form is an effective microbial pesticide; purified toxin from this strain is the world's most widely used biochemical biopesticide, and the genetic material encoding the *Bt* toxin makes powerful plant-incorporated protectants as well (Olson, 2015).

Microbial pesticides are obtained from naturally occurring or genetically altered bacteria, fungi, algae, viruses, or protozoans. They suppress pests either by producing a toxin specific to the pest and thereby causing disease, or by preventing the establishment of other microorganisms through competition, or by various other mechanisms of action. Biochemical pesticides are closely related to the conventional chemical pesticides. However, they are distinguished from conventional pesticides by their nontoxic mode of action of target organisms (as they are usually species-specific) and their natural occurrence. In the case of biopesticide formulations, it might be a registered biochemical or microbial pesticide that contains one or more active ingredients from the categories described above. The active ingredient(s) is primarily responsible for the pesticidal activity. In addition to the active ingredient, the product formulation contains one to several other inert ingredients. Plant-incorporated protectants are genetically modified plants that synthesize the pesticidal substances for the desired activity. The current advancements in recombinant DNA technologies have contributed to modern agriculture through the development of plant-incorporated protectants. However, the potential risks of genetically engineered plant-incorporated protectants have to be examined in view of numerous factors, such as risks to human health, nontarget organisms, the environment, potential for gene flow, and the need for insect resistance management plans (EPA, 2015). It is beyond the scope and context of this chapter to outline the genetically engineered plant-incorporated protectants here due to the strong advocacy for natural indigenous resources as biofertilizers. The types of biopesticides and their characteristics have been tabulated in Table 9.3.

9.3.2 Mode of Action of Biopesticides in the Soil

The major feature that differentiates biopesticides from synthetic chemical pesticides is their mode of action. Many biopesticides have various modes of action such as disruption of mating, antifeeding, suffocation, and desiccation, while most of the chemical insecticides are neurotoxic to pests (Olson, 2015). The most commonly used biopesticides are *Bt*, baculoviruses, and neem. In addition to these, *Trichoderma* and *Trichogramma* are also frequently used. *Trichoderma* is a fungicide and *Trichogramma* is a biobased control agent

TABLE 9.3

Types of Biopesticides and Their Characteristics with Examples

Types and Subtypes		**Characteristics**
Microbial pesticides		
Bacterial	Insecticide, e.g., *Bacillus thuringiensis* (Bt)	Target pests are moths and butterflies specifically
	Bactericide, e.g., *Bacillus subtilis* (Bs)	Target pests are bacterial and fungal pathogens (*Rhizoctonia*, *Fusarium*, *Aspergillus*, and others)
	Fungicide/bactericide *Pseudomonas fluorescens*	Used to control many fungal, viral, and bacterial diseases
Fungal	Insecticide, e.g., *Beauveria bassiana*	Used to control foliar feeded insects
	Fungicide, e.g., *Trichoderma viride/harzianum*	Used to control soil-borne fungal diseases
	Fumigant, e.g., *Muscodor albus*	Used to control bacterial and soil-borne diseases
Viral	Insecticide, e.g., Nucleopolyhedrosis virus	Used to control specific species of Lepidoptera (88%), Hymenoptera (6%), and Diptera (5%)
	Insecticide, e.g., Granulosis Virus	Used to control specific species of Lepidoptera
Others	Biological controls	Microscopic and macroscopic predators are used in integrated pest management systems
Biochemical pesticides		
Insect pheromones	Production of message-bearing substances from plant or animal sources	It does not kill the target pest. Mainly used to attract insect toward trap or disturb mating
Plant extracts and oils	Insecticides/herbicides, e.g., pyrethrum	Used to kill insect or paralyzes quickly by altering the electrical impulse
Plant growth regulators	Auxins, e.g., Indole-3-butyric acid	Used to shoot elongation for fruit trees
	Gibberellins, e.g., gibberellic acid	Used for stimulating the cell division and elongation in fruit trees
	Cytokinins, e.g., kenetin	Used for stimulating cell division especially in bud initiation
	Ethylene and ethylene generators	Used for increase the ripening activity
	Growth inhibitors and retardants, e.g., abscisic acid	Used to shortening the internodes specifically flower production
Insect growth regulators	Juvenile hormone-based insecticides	Disturbs the emergence of adult and formation of immature
	Chitin synthesis inhibitors	To control the production of new exoskeleton after molting
Biopesticides formulations		
Inerts	Inert ingredients are grouped into four types based on toxicological concern, priority for testing, new toxics, and least toxic concern	Effectiveness is based on target pest attachment or absorption of active ingredient or died after eaten the inerts Main reasons behind the adding inerts in product formulations are increased performance, ease mode of apply, spreadability or stickiness in plant leaves and soil, and solubility

for parasites, as they are the predators of pests and their eggs. In general, biopesticides destroy pests either by producing a toxin or causing the disease, or competing with others to predominantly flourish. The specific mode of action of these biopesticides and biocontrol agents are briefly described below: *Bt* is mainly used against the pathogen of lepidopterous pests that includes American bollworm in the case of cotton and stem borers in rice crops (Gupta and Dikshit, 2010). The mechanism of action of a *Bt*-based biopesticide depends on the release of toxins after it has been ingested by the pest larvae. The toxins damage the midgut of the larva, finally killing the pest and protecting the crop from attack. However, it is important that the pH of the midgut should be alkaline for the appropriate action of biopesticides and the specific gut membranes bind strongly with the toxin.

Baculoviruses are target-specific viruses that infect and destroy numerous import plant pests under the category of lepidopterous pests of cotton, rice, and vegetables. They are widely used as insect pest control agents as well as protein expression vectors. Baculoviruses do not replicate in vertebrates, plants, and microorganisms. Their host range is generally limited to arthropods and most particularly insects. To date, most of the registered baculovirus products are for control of lepidopteran and sawfly forest pests (Rohrmann, 2013). The mode of operation of baculoviruses follows a complex replicative cycle for virus production through effective protein synthesis by seizing and diverting the metabolic mechanism of the host cell (Hubbard et al., 2014). The benefits and drawbacks of baculoviruses as insecticides and the recent progress made in genetic enhancement of baculoviruses for improved insecticidal efficacy have been reviewed in detail elsewhere (Popham et al., 2015).

Neem tree (*Azadirachta indica*) is a natural source of numerous chemicals that exhibit antipest properties. For instance, the popularity of "azadirachtin" that affects the reproductive and digestive systems of some important pests has led to the development of effective formulations of neem that are commercially produced. Due to their nontoxic and noncarcinogenic nature, there is an enormous upsurge in the demand for the neem-based biopesticides, which has further led to its intensive industrialization.

Trichoderma is an effective fungicide for dryland crops such as groundnut, black gram, green gram, and chickpea, which are susceptible to soil-borne diseases such as root rot (Chandler et al., 2011). The principal mode of action of *Trichoderma* was presumed to exhibit either competition for space and resources or antibiosis and mycoparasitic (Harman, 2006). However, these fungi exhibit localized resistance through the released bioactive molecules by colonizing the root epidermis and outer cortical layers of the plant. Likewise, the fungi could act as biocontrol agents through various modes of a mechanism such as enzyme inhibition, competition for nutrients, and opportunistic plant symbionts. *Trichogramma* is effective against pests of vegetables and fruits and lepidopteran pests like the sugarcane internode borer, pink bollworm, and sooted bollworms in cotton and stem borers in rice. The mode of action of *Trichogramma* is through laying of eggs on various lepidopteran pests and the larvae then feed on and destroy the host eggs.

9.4 Scope of Biofertilizers and Biopesticides

The recent decades have witnessed a slow but steady rise in the industrial activities associated with biofertilizers and biopesticides as a potential supplementary and ecofriendly input to their chemical counterparts. In order to nullify (or respond to) the damages caused by the insect pests, the plants have started synthesizing specific secondary plant chemicals.

It could be highly possible as the plants and insects have simultaneously evolved in the biosphere for millions of years. Hence, the development and implication of botanical pesticides (originating from the plants) is one of the easiest and viable alternatives to the intensified use of chemical fertilizers as they are ecofriendly, economical, and effective against pests. Those bioactive chemicals include a wide array of types such as insecticides, antifeedants, insect growth regulators (IGRs), hormones, repellents, attractants, and so on. Therefore, natural pesticides from plants should be treated as an important alternative source for chemical pesticides. The acknowledgment of scope of bioactive plant species rekindled the quest for search of new bioactive plant species. To date, the selection of bioactive plant species was based on random screening, phytochemical targeting, ethnobotanical survey, chemotaxonomic approach, and targeted screening approach (Charles, 2011). Over the years, more than 6000 species of plants have been screened and nearly 2400 plants belonging to 235 families have been found to possess significant biological activity against insect pests (Saxena, 1998; Koul and Walia, 2009). Till date, around 2500 bioactive plant species, over 1000 protozoa pathogenic organisms to prevent insect attack, 750 fungal species to avoid attack of terrestrial and aquatic arthropods, baculovirus that can infect over 700 species of invertebrates, and a wide array of other microbial agents and macrobiological agents have been documented (Raj Paroda, 2009). These bioagents and their role in sustainable agriculture should be highlighted further in order to encourage future generations to adopt agricultural economy in a sustainable way. There are approximately 400 registered biopesticide active ingredients and over 1250 actively registered biopesticide products in the market (Raja, 2013). Table 9.4 lists the limited commercially explored biocontrol agents and their uses with examples.

Surprisingly, there was limited number of research and development as well scientific publications on biopesticides until the early 1990s. However, globally, biopesticides witnessed a significant growth in research and commercialization after 2000 due to serious recognitions of the long-term ill effects of unprecedented utilization of chemical fertilizers and pesticides as well as due to a rising demand for organic agricultural products from Western countries. In the last decade, the focus has shifted toward development of newer and safer pesticides for agricultural uses. Research on biopesticides has been dominated by microbial pesticides, particularly *Bt* research (Sinha, 2012). For all crop types, bacterial, fungal, viral, predator, and other biopesticides claim about 74, 10, 5, 8, and 3% of the market, respectively (Thakore, 2006). Moreover, there is an enormous upsurge in reverting to traditional indigenous systems in farming activities due to the realization of adverse impacts of chemical fertilizers and its injudicious use. As an outcome, intensive research activities are being carried out, and several products have also been made available in the global market.

9.4.1 Global Biofertilizer and Biopesticide Market

Recently, the market potential of biofertilizer- and biopesticide-based industries has been accelerating due to intensified utilization in current agricultural practices and increased demand for organic produce globally. Based on the report by Markets and Markets (2016), the worldwide biofertilizers market is expected to reach USD 1.88 billion by 2020 at a compound annual growth rate (CAGR) of 14.0% from 2015 to 2020. Based on the biofertilizer product types, the market has been segmented as nitrogen-fixing, phosphate-solubilizing, potash-mobilizing, and others (zinc, boron, and sulfur-solubilizing biofertilizers). The market has been fragmented based on the crop types, as cereals and grains, pulses and oilseeds, fruits and vegetables, and others. The minor categories such as turf and ornamentals, plantation crops, fiber crops, spices, silage, and forage crops were deliberated in the *Others*

TABLE 9.4

List of Commercially Explored Biocontrol Agents and Their Uses with Examples

Biocontrol Agents	Pests	Crops
Bacteria		
Bacillus popilliae	Japanese beetle, (Popillia japonica), milky diseases of beetles (coleoptera)	
Bacteriophages of *Xanthomonas* sp. and *Pseudomonas syringae*	Bacterial spot in pepper and tomatoes and bacterial speck in tomatoes	Tomatoes and pepper
Pseudomonas syringae strain ESC 10	Ice inducing bacteria and biological decay	Apples, pears, lemons, oranges, or grapefruit after the fruit is harvested
Pantoea agglomerans strain E325	Fireblight (*Erwinia amylovora*)	Apples and pears
Virus		
Coding moth granulosis virus	Coding moth	Apple, pear, walnut, and plum
Cabbage army worm nuclear polyhedrosis virus	Cabbage moth, American bollworm, diamondback moth, potato tuber moth	Cabbage, tomatoes, cotton
Spodoptera littoralis	*Spodoptera littoralis*	Cotton, corn, tomatoes
Helicoverpa zea	*Helicoverpa zea*, and cotton bollworm, *Heliothis virescens*, tobacco budworm	Cotton and vegetables
Spodoptera exigua	Beet armyworm (*Spodoptera exigua*)	Vegetable crops, greenhouse flowers
Anagrapha falcifera	Celery looper (*Anagrapha falcifera*)	Vegetables
Autographa californica	Alfala looper (*Autographa californica*)	Alfalfa and other crops
Orgyia psuedotsugata	Douglas fir tussock moth (*Orgyia psuedotsugata*)	Forest habitat, lumber
Lymantria dispar	Gypsy moth (*Lymantria dispar*)	Forest habitat, lumber
Fungi		
Bacillus pumilus QST 2808	Rust, powdery mildew, cercospora, and brown spot	Soybeans, cereal crops, and potatoes
Coniothyrium minitans strain CON/M/91-08	*Sclerotinia sclerotiorum, Sclerotinia minor*	Agricultural soils
Bacillus subtilis GB03	*Rhizoctonia, Fusarium, Alternaria, Aspergillus*, and others that attack the root systems of plants	Cotton, peanuts, soybeans, wheat, barley, peas, and beans
Trichoderma harzianum Rifai strain KRL-AG2	*Fusarium, Pythium*, and *Rhizoctonia*	Flowers, ornamentals, fruiting vegetables, herbs, and spices, hydroponic crops, leafy vegetables, cole crops, pome fruits
Bacillus subtilis strain QST 713	Fire blight, botrytis, sour rot, rust, bacterial spot, and white mold	Vegetables, fruit, nut, and vine crops
Bacillus pumilus QST 2808	Fungal pests such as molds, mildews, blights, and rusts	Many food and nonfood crops, including trees susceptible to sudden oak death syndrome

category. On the basis of microorganisms, the biofertilizers market has been segmented as *Rhizobium*, *Azotobacter*, *Azospirillum*, *Cyanobacteria*, PSB, and others (potash-mobilizing, zinc biofertilizers, sulfur-solubilizing biofertilizers, and manganese solubilizers). Based on the application type, the biofertilizers market has been segmented as seed, soil, and others (set treatment, foliar treatment, root dipping, and seedling root treatment). On the basis of region, the biofertilizers market has been segmented as North America, Europe, Asia-Pacific, Latin America, and rest of the world (Markets and Markets, 2016).

Currently, the nitrogen-fixing biofertilizer category holds the largest market share in global biofertilizer market and is expected to grow at a CAGR of 13.25% till 2020. The second largest market share is from phosphate-solubilizing biofertilizer segment and expected to rise at a CAGR of 20.75% till 2020. Further, these trends were expected to follow till the projected time. In case of biofertilizer marketing potential by microorganism type, Azospirillum-based biofertilizers currently control the largest market share in the global biofertilizer market. The global Azospirillum biofertilizer market is expected to grow at a CAGR of 17% till 2020. The second largest market share in this category is from *Azotobacter* type and expected to grow at a CAGR of 11% till 2020. In terms of biofertilizer marketing potential by crop type, cereals and grains currently control the largest market share in the global biofertilizer market in terms of consumption. The global cereals and grains biofertilizer market is expected to grow at a CAGR of 13% till 2020. Based on the terms of geographical locations, the North American biofertilizer market controls the largest market share of the global biofertilizer market. The market share is expected to grow at a CAGR of 16.65% till 2020. Next to North American market share, European biofertilizer market is expected to grow at a CAGR of 14.90% till 2020. Globally, the third largest market share is the Asia-Pacific biofertilizer market and expected to register second largest growth rate of 11.40% till 2020 (Business Wire, 2016).

Based on the report by Markets and Markets (2016), the biopesticide market is projected to reach USD 6.6 billion by 2020 and is expected to grow at a CAGR of 18.8% from 2015 to 2020. Based on the biopesticide product types, the global market has been segmented as bioinsecticides, biofungicides, bioherbicides, bionematicides, and others (sulfur, oil, insect repellent, moth control, and other biochemicals). The market has been fragmented based on the crop types, as cereals and grains, pulses and oilseeds, fruits and vegetables, and others. The minor categories such as turf and ornamentals, plantation crops, fiber crops, spices, silage, and forage crops were deliberated in the *Others* category. On the basis of origin, the biopesticide market has been segmented as beneficial insects, microbial pesticides, and biochemicals. The biopesticide market has been classified as liquid formulation and dry formulations on the basis of formulation type. Based on the application type, the biopesticide market has been segmented as foliar spray, seed treatment, soil treatment, and postharvest category. On the basis of region, the biopesticides market has been segmented as North America, Europe, Asia-Pacific, and rest of the world such as Brazil, Argentina, and South Africa (Markets and Markets, 2016). Currently, the major share of the global biopesticide market is from North America, but Europe is expected to show the highest growth rate during the forecast period. However, developing regions such as Asia-Pacific and South America are also expected to grow significantly during the forecast period. The biopesticides market in Asia-Pacific is expected to increase globally by CAGR of 17.8% during 2015–2020 (Research and Markets, 2016).

9.4.2 Production of Biofertilizers and Biopesticides

Increase in the demand for the biofertilizers in the recent decades have paved the way for new entrepreneurs into biofertilizer production. The strategy involves choosing active microbes, isolation, and selection of target microbes, selection of propagation methods and appropriate carrier materials, prototype testing, and large-scale testing. The first step involves the selection of active microbial species based on the purpose of fertilizing property and crop requirements. For instance, one should decide on whether to use organic acid-secreting bacteria or nitrogen fixer or a combination of few organisms. Then, isolation of the target microbes from their actual habitation is carried out. Figure 9.4 outlines the strategies in synthesizing biofertilizers.

In general, microorganisms are usually isolated from plant roots or are trapped using other organic materials. Further, the isolated organisms would be subjected to the general bioprocess development that involves a series of steps. The isolated microbes will be grown first on Petri plates, then in a shaker flask, and finally on a laboratory-scale fermenter before proceeding to actual field-level implementation to select the best organisms and optimize influencing parameters. Growth conditions could be experimented using shaker flask experiments to optimize the medium, while fermentor-based experiments are used to optimize operating conditions. Since bacteria are extremely perishable and sensitive to

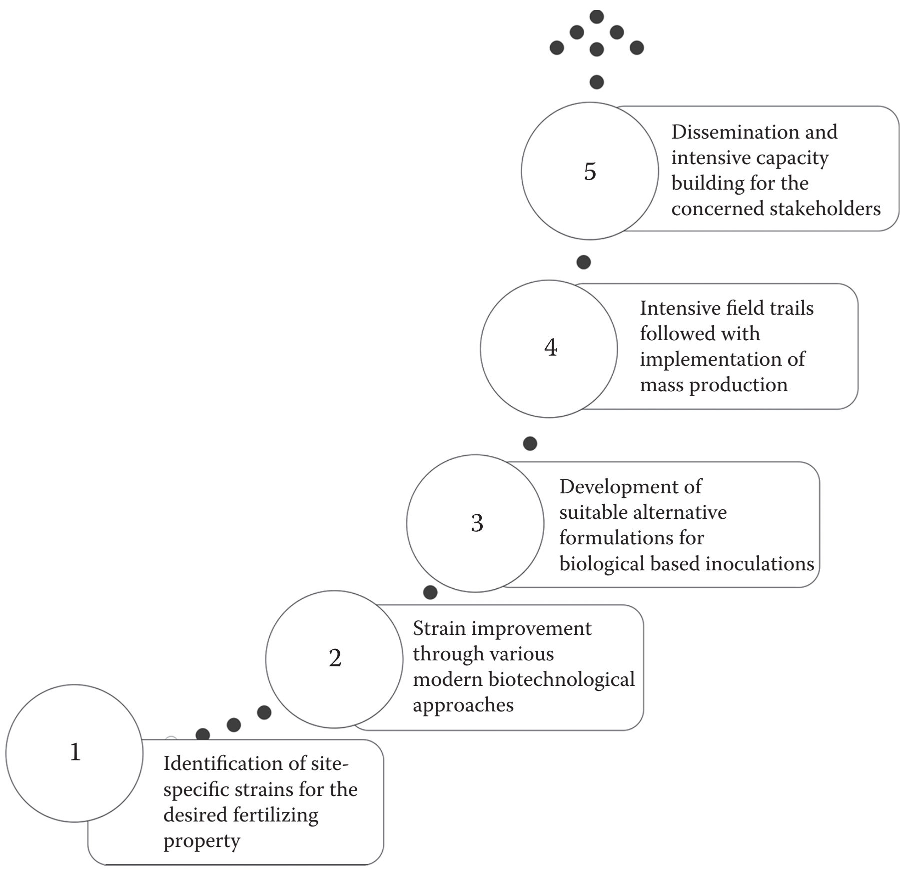

FIGURE 9.4
Strategies in synthesizing biofertilizers.

environmental factors, there is always a need for developing efficient and resistant strains that can withstand local ecological conditions, replenish soil fertility, and improve nutrient uptake by plants. At this stage, it is quite imperative to decide the form of the biofertilizer product wisely so that the right carrier material could be recommended. For instance, if biofertilizer in powder form is desired, then organic materials such as tapioca flour or peat could be used as carriers. Incorporation of microbes in the carrier material enables easy handling, long-term storage, and high effectiveness of biofertilizers. Sterilization of carrier material is crucial for maintaining high concentrations of inoculant bacteria on the carriers for long storage periods. Gamma irradiation or autoclaving can be used as a method of sterilization.

While selecting the propagation method, it is equally important to find out the necessary optimum conditions for the growth of the isolated organisms. It could be achieved by obtaining a growth profile by varying several influencing parameters and all other environmental conditions. Finally, a prototype (usually in different forms) is made and tested before proceeding with large-scale testing at various environmental setups to scrutinize effectiveness and limitability. Although many microbial species can be used beneficially as biofertilizers, the technique of mass production is standardized for very few particular strains such as *Rhizobium*, *Azospirillum*, *Azotobacter*, and *Phosphobacteria*. However, the survival of the inoculant strains depends on various influencing factors such as soil composition, physiological status, temperature, pH, and moisture content. Several biotic factors contribute to competition; predation and root growth also affect the survival of the inoculated strains.

Most of the biocontrol agents are quite stable in dry form, as they are free from water and extremes of heat. Basically, liquid biofertilizers have been classified into two types: dry products (dust, granules, and briquettes) and liquid suspensions (oil or water-based and emulsions). Liquid formulations are a sprayable form of the microbial agents suspended in suitable liquid medium to maintain their viability for the stipulated time that enhances the biological activity of the target site. In the case of flowable liquid formulations, the products are quite sensitive to heat and must be protected during storage to avoid settlability of active ingredients. Hence, the shelf-life of flowable formulations is much shorter than that of dry formulations. The formulation should have the following basic characteristics:

- Stabilization of the microorganisms during production, distribution, and storage of the product.
- Easy deliverable to the target site (field) on time.
- Exhibiting perseverance at the target site (field) through the protection of the microorganisms from adverse environmental factors.
- Enhancement of the microorganism's activity at the target site by increasing its viability, reproduction, contact, and interaction with the target crops (Pindi and Satyanarayana, 2012).

9.4.3 Criteria for Ensuring the Quality of Biofertilizers and Biopesticides

Biofertilizers could be formulated either as a carrier- or noncarrier-based microbial inoculants. In addition to the active microbes, several other amendments such as carriers, fillers, and extenders have been utilized in experimental and commercial formulations of various biocontrol agents. Amendments are specifically added to

TABLE 9.5

List of the Amendments with Examples

Purpose of the Amendments	Examples
Binders	Gum arabic, carboxymethylcellulose
Desiccants	Silica gel, anhydrous salts
Nutrients	Molasses, peptone
Stabilizers	Lactose, sodium benzoate
Surfactants	Tween 80
Thickeners	Xanthan gum
Carriers	
Liquid carriers	Vegetable oils
Mineral carriers	Kaolinite clay, diatomaceous earth
Organic carriers	Grain flours
UV protectants	
Dispersants	Microcrystalline cellulose
Light blockers	Lignin
Optical brighteners	Blankophor
Stickers	Pregelatinized corn flour
Sunscreens	Oxybenzone

improve the physicochemical and nutritional properties of the formulated biocontrol agents. A few amendments along with limited examples are tabulated in Table 9.5.

Most of the times, carrier-based preparations are typically followed in the case of microbial inoculants for nitrogen-fixing or phosphate-solubilizing activities, since their prolonged persistence in soils is vital. A good quality carrier material for microbial inoculants should consist of carbon, nitrogen, and vitamin sources, which can promote growth and survival of bacteria (Bashan, 1998). Compost is one such carrier material that has these characteristics. Organic carrier materials are the most cost-efficient carriers for the preparation of microbial inoculants due to their widespread availability. The solid inoculants carry a number of microbial cells and support the survival of these cells for longer periods of time. The mass production of carrier-based microbial biofertilizers involves three stages: culturing of the desired microorganisms, processing of the carrier material, mixing the carrier and the broth culture, and, finally, packing in an appropriate container for the desired purpose. However, before proceeding with the mass production of carrier-based microbial biofertilizers, the selection of carrier materials should be ensured for the following criteria: nontoxic to the plant as well as microbial inoculant strain(s), cost-effective and ubiquitous, easy to process, and sterilization. In addition, the carrier materials should have good moisture absorption and pH buffering capacity. Likewise, the selection of microbial inoculants for biofertilizer applications should satisfy the following criteria:

- ability to fix atmospheric N_2 over a broad range of varying environmental conditions of the soil
- ability to compete with other potent microbial strains
- ability to multiply in a liquid culture medium and survive in dormant stage in the carrier as well as in seed pellets
- ability to persist in soil and to form nodules

- ability to continue to fix atmospheric N_2 in the presence of soil nitrogen
- ability to migrate beneath the soil and to colonize the microbes present in the roots of the plant
- ability to be stable during storage

These criteria have to be fulfilled before proceeding with the mass production and application in the field level. Similar kind of criteria for selecting the appropriate microbial consortium cultures in view of biopesticide applications are as follows: ability to compete with other microbial strains present in the soil; ability to control pests; ability to maintain ecological balance; ability to sustain the productivity of the soil; and so on.

9.5 Limitations of Using Biofertilizers and Biopesticides

If given the right impetus, biopesticides and biofertilizers could pave the way for sustainable agriculture. However, their use has not reached significant levels due to various natural and odd reasons. The market share of most of the biocontrol agents is very meager. However, in the case of seedling disease, root rot, and postharvest disease control, the market share are competing with synthetic fungicides. Yet, effective biocontrol agents have not been identified for the control of serious foliar diseases such as grape downy mildew, potato late blight, wheat powdery mildew, and apple scab (Froyd, 1997). Therefore, in addition to routine bioprospecting aspects of novel biocontrol agents, several strategies have to be adapted for scale-up of the demonstrated biocontrol agents. A thorough investigation is needed at regional and global level to discuss the issues that have to be resolved to promote their use for sustainable agriculture.

Biofertilizers that contain useful enzymes and microbes could increase plant growth and quality of crops, as well as reduce the cost of fertilizer and pesticide applications (Chen, 2006; Zarei et al., 2012). Since the production technology of biofertilizers is relatively simple, the installation capital cost is very low compared with that of the chemical fertilizer plants (Chen, 2006; Wong et al., 2015). Biofertilizers are low-cost renewable source of nutrient that supplements the chemical fertilizer and gaining attention from small and marginal farmers (Bhattacharjee and Dey, 2014). The cost-effectiveness of biofertilizers and biopesticides invites lot of debates in view of several dimensions. This could be due to the fact that several factors on environmental economics are not being considered in the techno-economical analysis. Recently, several studies have reported the cost–benefit analysis of commercially available biofertilizers and biopesticides. For instance, Jefwa et al. (2014) evaluated over 80 microbial inoculant products on major legumes, cereals, and banana crops across diverse agro-ecological conditions in Ethiopia, Nigeria, and Kenya at both laboratory and field conditions. The study revealed around 30% increase in the yield and benefit–cost ratio of almost five. The efficient utilization of locally available indigenous natural resources for the fertilizing activities should be promoted for the sustainable use of biofertilizers and biopesticides. For instance, if a farmer utilizes his locally available natural bioresources for fertilizing and pesticiding activities, the manufacturing cost will be low. Further, it minimizes the overall cost of the product due to less money spent on managing the costs such as transport, storage, dealership, and so on. Even in the case of synthetic formulations of microbial inoculants, the cost-effective organic carrier materials are most efficiently utilized due to the widespread availability of natural renewable resources. Since the key ingredients (inputs) for biofertilizers were demonstrated to be cost effective, the ease availability and standard quality of biofertilizers could resulted in intensive usage at grass root levels. Two reasons were reported to be important for the discontinuation of use of biofertilizers in India: availability and quality. Both of these issues could be addressed by promoting the utilization of regionally available natural bioresources at grassroot levels. The cost-effectiveness of biofertilizers and biopesticides could be comprehended well with the few following cited examples, but are not limited to

1. Though the direct application of raw organic wastes such as solid urban waste, food factory waste, sewage sludge, agricultural residues, and domestic waste are inappropriate for land and agricultural production (Ahmad et al., 2007), their utilization in land application has emerged as an attractive and cost-effective strategy in recent decades due to its richness in organic content for composting. These wastes have been demonstrated to supply plant nutrients and organic matter to the soil for efficient crop production. Unlike fast-release chemical fertilizers, these organic wastes minimize the cost of purchasing nonorganic fertilizers and the environmental impact associated with fertilizer production and use (Vakili et al., 2015; Zendejas et al., 2015).
2. The application of PSB such as *Bacillus megatherium* var. *phosphaticum* enhanced the phosphate availability of the soil by increasing the PSB population in the rhizosphere. While used in conjunction with phosphate fertilizers, PSB reduced the required phosphate dosage by 25%. In addition, 50% of costly superphosphate could be replaced by a cheap rock phosphate, when applied in combination with PSB (Sundara et al., 2002; Chen, 2006).

Yet, the biopesticides are largely regulated by the protocols developed for chemical pesticides. Several technological and policy gaps have to be addressed to avoid the imposition of burdensome costs on the biopesticide industry under this situation. A proper regulatory system should be developed to balance the broadly defined costs and benefits of biopesticides compared with synthetic pesticides (Kumar and Singh, 2014). To summarize, several optimistic studies on paradigm shift for the rejuvenation of biofertilizers and biopesticides for sustainable agriculture were reported with the cost—benefit analysis. Though biofertilizers seem to be a cost-efficient and ecofriendly technology, several constraints limit their application, and they are highlighted in Table 9.6.

Biofertilizers could not completely replace but complement conventional chemical fertilizers. Due to the low nutrient density of biofertilizers, the quantum, frequency, and application procedures might differ based on site-specific conditions. Usually, they require long-term storage and, therefore, careful maintenance of the activeness of the inocula is essential. Also, extreme soil conditions like too hot or dry, acidic or alkaline, might influence the efficacy of biopesticides if other microorganisms contaminate the carrier medium. Moreover, biological control agents are less effective if the soil contains an excess of their natural microbiological predators.

While implementing the biofertilizer technology, various constraints regarding environmental, technological, infrastructural, financial, human resources, awareness, quality, and marketing are being discussed in public domains. These numerous constraints might affect the production techniques severely and trigger the alteration in marketing and/or their

TABLE 9.6

List of the Constraints for Using Biopesticides and Biofertilizers in Agriculture

Constraints	Purpose of the Constraints
Technology	• Use of improper, less-efficient strains for production • Lack of qualified technical personnel in production units • Unavailability of good-quality carrier material or use of different carrier materials by various producers without knowing the quality of the materials • Production of poor quality inoculants without understanding the basic microbiological techniques • Short shelf-life of inoculants
Infrastructure	• Nonavailability of suitable facilities for production • Lack of essential equipment, power supply, etc. • Space availability for laboratory, production, storage, etc. • Lack of facility for cold storage of inoculant packets
Finance	• Nonavailability of sufficient funds and problems in getting bank loans • Less return by sale of products in smaller production units
Environment	• Seasonal demand for biofertilizers • Simultaneous cropping operations and short span of sowing/planting in a particular locality • Soil characteristics like salinity, acidity, drought, water logging, etc.
Human resources	• Lack of technically qualified staff in the production units • Lack of suitable training on the production techniques • Ignorance on the quality of the product by the manufacturer • Nonavailability of quality specifications and quick quality control methods • No regulation or act on the quality of the products • Lack of awareness of the technology and its benefits • Problem in the adoption of the technology by the farmers due to different methods of inoculation • No visual difference in the crop growth immediately as that of inorganic fertilizers
Dissemination and capacity building	• Unawareness on the benefits of the technology • Problem in the adoption of the technology by the farmers due to lack in hands-on training on various methods of inoculation • Lack of technically qualified personnel to train the end users • Unawareness on the damages caused on the ecosystem by continuous application of inorganic fertilizer
Market	• Nonavailability of right inoculant at the right place in right time • Lack of retail outlets or the market network for the producers

Source: Entrepreneurial Training Manual, TNAU Agritech Portal.

further usage. Despite encouraging results, microbial inoculants-based biofertilizers have not got a widespread application in agriculture. This is mainly about the choice of bacterial strain used, the responses of plant species vary under unfavorable rhizosphere conditions. On the other hand, real competitive ability and high saprophytic competence are major factors determining the success of a bacterial strain as an inoculant. Therefore, studies to find out the competitiveness and persistence of specific microbial populations in complex environments, such as the rhizosphere, should be carried out to obtain efficient inoculants. The key critical factors responsible for effectiveness of biofertilizers discussed by Kalra and Khanuja (2005) are as follows:

- Host specificity and suitability of the species for the target crop.
- Identification of strains suited to the agroecosystem, particularly the soil pH and moisture conditions.

- Significant cell count of living organisms presents on the product, its purity, and its level of contamination.
- Conditions of the carrier material in which the culture is packed and the quality of the packing material, which determines the shelf-life.
- Appropriate packing, storage, and distribution of the product by stakeholders before application (Teng, 2007).

Further, several other factors also limit the extensibility of biofertilizers and biopesticides in real-time applications. Though several microbial strains have been shown to enhance the agricultural productivity on a laboratory scale, only few strains could be acclimatized for real-time scenarios. Precisely, the limited availability of active microbes with field-level testing and the appropriate growing nutrient medium are the two key issues that hinder the commercial availability of these biofertilizers in the market.

9.6 Integrated Nutrient Management and Integrated Pest Management

Integrated nutrient management (INM) and integrated pest management (IPM) are the two key driving forces for biopesticides and biofertilizers, as they are cost-efficient and renewable source for sustainable agriculture. Much attention is now being paid to develop an INM system that maintains or enhances soil productivity through the balanced use of all sources of nutrients—including chemical fertilizers, organic fertilizers, and biofertilizers. The basic concept underlying INM is the adjustment of soil fertility and plant nutrient supply to an optimum level for sustaining desired crop productivity through optimization of the benefits from all possible sources of plant nutrients in an integrated manner. Further, the implementation of IPM ensures a healthy ecosystem to enhance the agricultural productivity (Tilman et al., 2002). While we are striving hard to accomplish rapid advancements on agricultural technology and devising sophisticated approaches for crop protection, the IPM could offers an alternative to evade the resistance and non-targeted problems associate with the usage of conventional chemical fertilizers and pesticides. IPM is a systematic approach that combines different crop protection practices along with a cautious monitoring of pests and their natural predators. The aim is to manage pest population below the levels that cause economic damage. The main components of IPM are pesticides with high levels of selectivity and low-risk compounds, breed of crop cultivars with pest resistance, cultivation practices (crop rotation, intercropping, undersowing), physical methods (mechanical weeders), natural products (semi-chemical, biocidal plant extracts), biological control with natural predators and microbial pathogens, informing farmers when it is economically beneficial to apply pesticides (timing of pest activity and scouting), and other controls. Thus, IPM is an example of sustainable intensification, defined as "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" (Pretty and Bharucha, 2014, 2015).

Organic farming practices aim to enhance biodiversity, biological cycles, and soil biological activity so as to achieve optimal natural systems that are ecologically and economically sustainable (Samman et al., 2008). Manure management is a decision-making process aimed at combining profitable agricultural production with minimal nutrient losses from manure. The selection of manure management and treatment options increasingly depends on environmental regulations for preventing pollution of land, water, and air (Karmakar et al., 2007).

In recent years, biofertilizers have emerged as a promising component of the INM system in agriculture. The entire structure of farming depends on microbial activities in many significant ways, and there appears to be a tremendous potential for making use of microorganisms in increasing crop production. Moreover, some microbes are helpful for plant growth in multiple ways, like *Azotobacter*, which help in both nitrogen fixation and stimulating root development. Microbiological fertilizers are an important component of ecofriendly sustainable agricultural practices (Bloemberg et al., 2000).

Soil microbes play an important role in many critical ecosystem processes, including nutrient cycling and homeostasis, decomposition of organic matter, and promoting plant health and plant growth through biofertilization (Han et al., 2007). Certain strains are referred to as plant growth-promoting rhizobacteria (PGPR), and these can be used as inoculant biofertilizers (Kennedy et al., 2004). They include species of *Azotobacter* and *Azospirillum*, both of which have direct and indirect effects on plant growth and pest resistance (Persello et al., 2003). Soil microorganisms such as *Azotobacter* and *Azospirillum* as N_2-fixing bacteria could be valuable sources to enhance plant growth and produce considerable amounts of biologically active substances that can promote the growth of the reproductive organs and increase crop productivity (Ebrahimi et al., 2007; Akbari et al., 2011; Singh et al., 2011). Biofertilizers enhance the productivity and sustainability of the soil, as they are low-cost, ecofriendly, and renewable source of plant nutrients. Therefore, they play a significant role in the sustainable agricultural system. In this context, biofertilizers can be considered as key components of INM (Mohammadi and Sohrabi, 2012).

Figure 9.5 outlines the several possible interactions between plants, pathogens, and the plants associated beneficial microbes. Competitive interactions between pathogens and beneficial microbes along with other significant interactions such as antibiosis (an antagonistic association between two microorganisms) for the prevention of growth or development of an organism by a substance or another organism play a crucial role in the overall health of the plant. However, plant growth and suppression of the plant-associated diseases could be ensured by integrated application of the biopesticides and biofertilizers. Since the plant-associated microbes support the essential macro- and micronutrients, integrating them along with hormonal stimulation enhances disease resistance. Thus, the implementation of INM and IPM would pave the way for sustainable agricultural practices along with environmental protection and human health. There are basically four types of IPM interventions: management of pesticide components, breeding of crop (or livestock), deployment of pheromones and/or release of parasites (or predators), and establishing the agro-ecological habitat (Pretty and Bharucha, 2015).

Based on scientific knowledge and a fundamental understanding of pest and plant nutrition, environmentally sound integrated biological pest control and INM systems, which emphasize on the use and integration of diverse methods such as cultural (crop rotation), physical (organic amendments, chemicals, microorganisms), and resistant hosts should be developed. Ideally, pest control and nutrient supply must be integrated into one system. Adequate research is crucial for the successful integration of biopesticides and biofertilizers as integrated crop management (ICM), where a practical approach is followed for crop production that includes IPM as a subentity. It is based on the understanding of complex balance between the environment and agriculture through the encapsulation of numerous basic components for management of crop, nutrients, pest, and lastly economics (Kumar and Singh, 2014).

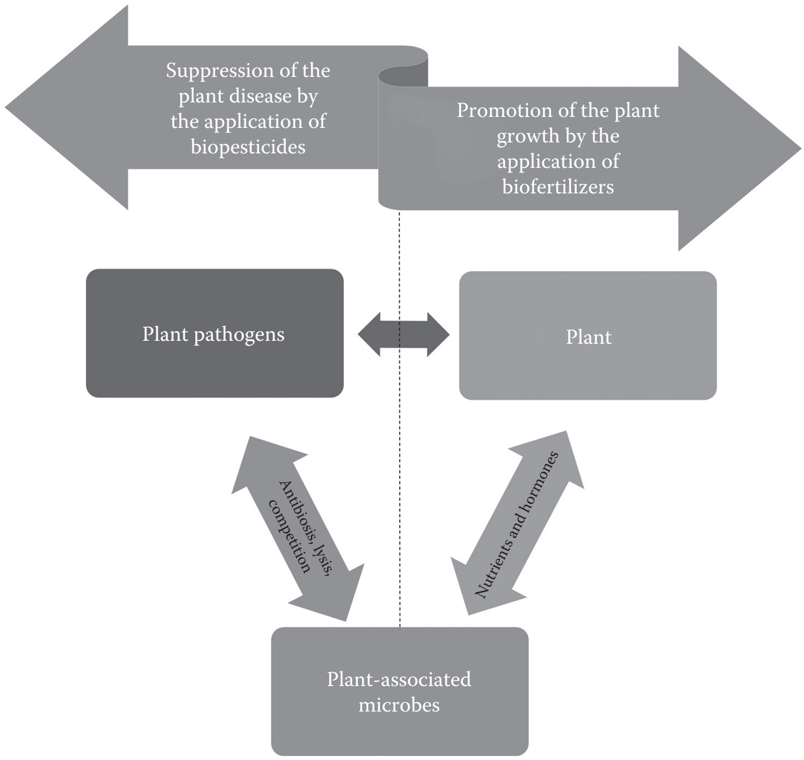

FIGURE 9.5
Role of biopesticides and biofertilizers in the several interactions among plants and microbes.

9.7 Role of Biofertilizers and Biopesticides in Sustainable Development

Since biopesticides emerged to address the major twin issues of crop protection while ensuring environmental sustainability, their role in overall sustainability is substantial. Enhancement in agricultural sustainability necessitates the optimal use and management of soil fertility and soil physical property and relies on soil biological processes and soil biodiversity. The integrated use of biofertilizers (for crop nutrition), biopesticides (for crop protection), and biostimulants (for crop enhancement) is the need of the hour for ensuring agricultural resilience. Hence, IPM should be treated as a subentity of sustainable agriculture, as the utilization of pest-control practices aids in enhancing the efficiency and economic viability of agricultural practices, environmental protection, and human health.

In general, sustainable development refers to the mode of human development through which resources are utilized wisely to meet the demands of both the current and future generations. Sustainable development tries to ensure sustainability in all three aspects of life: environment, economy, and socio-politics. More specifically, economic viability extends to economic growth across generations. While extending this paradigm to sustainable agriculture, it could be defined as the application of ecofriendly farming principles to enhance crop production without damaging the natural biotic and abiotic resources. Thus, the term sustainable agriculture represents an integrated system of site-specific plant and

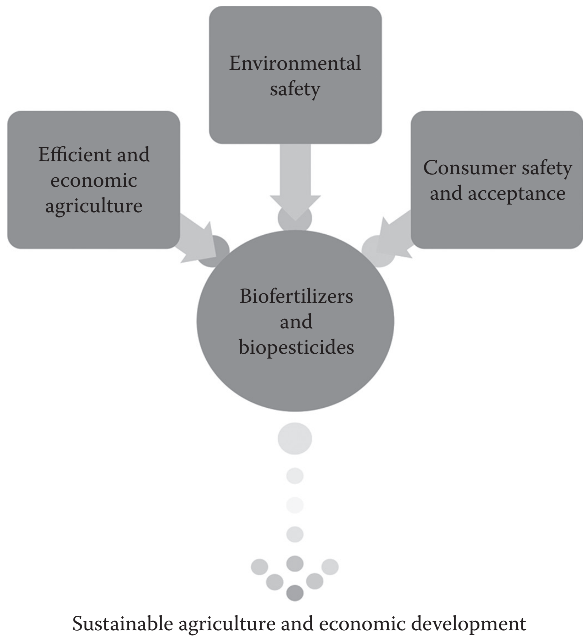

FIGURE 9.6
Role of biofertilizers and biopesticides in sustainable development.

animal production as well as manure management practices. The role of biofertilizers and biopesticides in promoting sustainable development is shown in Figure 9.6.

This concept of sustainable agriculture warrants sustainability in all three aspects across generations to fulfill human needs, enhance environmental quality, and sustain the economic viability of farm operations. For instance, instead of promoting economy at the cost of the environment, as with the current way of development, the implementation of sustainable agriculture would ensure the promotion of both economy and environment in a win–win situation. This could be achieved through well-planned management strategies that help the producer select hybrids and varieties through soil-conserving cultural practices, soil fertility programs, and pest management programs. The goal of sustainable agriculture is to minimize the adverse impacts while providing a sustained level of production and profit. Recently, the confluence of economy and environment through promoting sustainable agricultural activities has contributed to the rise of a new paradigm called sustainable agriculture economic development (SAED). Pallabi and Debiprasad (2014) demonstrated that the utilization of Azolla as biofertilizer is significantly greater than chemical fertilizer and showing better SAED.

The application of microbial inoculants-based biofertilizers is a natural and efficient way to enhance and promote the mineral economy of the soil. Biofertilizers could not be treated as a complete replacement for chemical fertilizers, rather they should be addressed as the next best alternative for the synthetic ones. The utilization of biopesticides lessens the utilization of chemical fertilizers and exploits the alternative for sustainable agriculture. In recent decades, there has been an expansion of research related to biofertilizers and biopesticides, since they act as natural stimulators of plant growth and development. Consequently, there has been considerable interest in the possible use of inoculants of effective microbes for the development of biofertilizers and biopesticides. Since the organic farming is one of the oldest forms of agricultural activities on the earth that still offers numerous benefits such as conservation of natural resources such as maintenance of soil fertility, water quality, prevention of topsoil erosion, and preservation of natural biodiversity, it could be advocated at grassroots levels. In view of social advantages, it aids in the generation of rural employment, improved household nutrition, and reduced dependence on external inputs. Further, it boosts the local economy through the high export potential of organic products. Thus, the practice of organic farming could also ensure the sustainability in all the three dimensions of society, economy, and environment.

9.8 Summary and Prospects

Agriculture has sustained human lives since the time of the ancient civilizations. With the rapid decline in agricultural farmlands due to the industrialization and rapid urbanization, modern agriculture inevitably continues to play a significant role in the survival of humanity. The diminishing quantity of finite natural resources to support agricultural activities are also under high stress, further fueling the need for adopting and implementing novel practices for sustainable agriculture. Efficient nutrition management should be ensured at all possible levels to enhance and sustain agricultural production while conserving the environment. Despite the sources of nutrient—chemical, organic, or microbial fertilizers—every type has its advantages and disadvantages. Hence, developing a suitable INM system based on these various kinds of fertilizers may be an extremely challenging task. On the other hand, one should not avoid the environmental consequences of pest management. Therefore, it is highly advisable to focus on IPM. INM and IPM should go hand in hand for a win–win situation to ensure the practice of sustainable agriculture. However, much research is still needed to address these challenges.

It is worth noting that biofertilizers are part of nature in the form of microorganisms that colonize the rhizosphere. Biofertilizers containing those microorganisms can play a significant role in crop improvement. Biofertilizers and biopesticides are a modern technology for global agriculture. It promises to overcome the limitations of conventional chemical-based technologies. In fact, it should be treated as a forgotten gift from nature to supplement modern agricultural activities. Biofertilizers and biopesticides are emerging products in the commercial market that are likely to sustain in the long run once sufficient scientific research and development has been done and the technological know-how has been disseminated to concerned stakeholders. Advocating the environmental paradigm of *think global and act local*, the utilization of biofertilizers and biopesticides at the regional level will not only have an impact on national agricultural productivity but also contribute to world economic development due to sustainable agriculture. There is also the undeniable fact that these holistic approaches contribute to the universal well-being of the world.

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