Chapter 17
Biofertilizers and Biopesticides: A Whole New Dimension for Ameliorating Soil Fertility and Organic Agriculture Practice

Meenakshi Rajput, V. Vivekanand, and Nidhi Pareek

Abstract In the forthcoming decades, maintaining food security, safety, and quality would impose a major challenge for the rapidly growing tropical countries. The excessive employment of the industrialized production methods has contaminated the food chain and water adversely so far by the continuous release of the harmful chemical residues of fertilizers and pesticides. Furthermore, the chemicals released amends the characteristics of the soil to highly acidic/alkaline that bring about the abatement in the number of beneficial soil microorganisms leading to the reduction in soil fertility and crop yields. Thus, to accomplish the aforementioned goals, it is highly desirable to move toward organic agriculture practices producing food with high quality and standards. The utilization of propitious microorganisms (PGPRs) as biofertilizers and biopesticides serves as better organic and eco-friendly alternative for the enhancement of soil fertility with efficient disease and pest control. Biofertilizers help in retaining the soil's macro and micronutrients, nitrogen fixation, antibiotic production, and phytohormone production and in the degradation of organic matter present in the soil. On the other hand, biopesticides are adeptly aid in pest control as they are comprised of the pathogenic microorganism specific to the pest of interest. Both biofertilizers and biopesticides offer ecologically and economically sustainable organic agriculture strategies with the assurance of an increase in soil biodiversity and the safety of food. The chapter highlights the microorganisms and their role in ameliorating soil fertility with the disease and pest control for sustainable organic agriculture.

Keywords Organic agriculture · Biofertilizers · Biopesticides · Microorganisms · Soil fertility

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17.1 Introduction

The world population will probably rise up to nine billion by 2050, indicating the urgent need for more food production to feed hungry mouths in the near future (Abbey et al. 2019). However, the practice of sustainable food production is still a major challenging task for the world as chemical-based fertilizers and pesticides are being used for crop production which ultimately imposes deteriorating effects on the environment as well as human health. The employment of these chemical fertilizers and pesticides has been accentuated in Indian agriculture by the commencement of the green revolution. The green revolution was a comprehensive collection of several valuable alternatives to enhance crop production such as high-yielding varieties (genetically engineered through modern breeding techniques), chemical-based fertilizers and pesticides, irrigation techniques (tube well and canal), and nutrient management (inorganic or organic). The appropriate utilization of the aforementioned techniques has amplified the crop yield and aided India to become self-sufficient during the hard times of the post-independence period (Singh et al. 2016). Despite the success of the green revolution in improving crop productivity across the globe, the utilization of chemical fertilizers has downgraded the quality of the soil. The chemical fertilizers increase the soil salinity that further obstructs the accessibility of micronutrients to the crops (Kumar 2018). At the same time, the chemical pesticides are also adding to environmental pollution as they are non-biodegradable and their continuous use making the insects resistant that further compelled the production of stronger pesticides. There are various other detrimental consequences of using chemical fertilizers and pesticides which include soil acidification, weakening of plant roots, high disease occurrence due to the death of healthy microorganisms and insects, and eutrophication of water bodies along with groundwater. This occurs because the chemical fertilizers or pesticides sprayed on the crops are not completely utilized by crops. For instance, the widely used chemical fertilizer, urea, when sprayed on the crops is partially used by crops, and remnants contaminate the water bodies through the runoff water (Kumar 2018). The water contamination through nitrate (urea) may lead to terrible ailments among the infants, viz. methemoglobinemia and hypertension, that in some cases make them handicapped also. Besides, the production of urea is even highly expensive as the production, transportation, and application of around 1 kg urea involve the expenditure of 1 L petroleum products. Therefore, it is clear that urea as fertilizer not only causes ill effects on the environment and mankind but is also not feasible economically (Pathak and Kumar 2016). In this regard, the organic framing serves as the best strategy to ensure food safety along with the replenishment of the soil biodiversity.

Nowadays, organic farming is receiving enormous attention globally from the scientific community as well as the public owing to the increased awareness about the harmful effects caused by the indiscriminate use of chemical fertilizers and pesticides. Interestingly, during the past two decades, the total area of organic farmland has been reported to reach up to 69.8 million hectares, and around 1.4% of total agricultural land is used for organic farming (Willer and Lernoud 2019).

Still, it is inexorable to address the ever-increasing demand for food worldwide without the use of chemical fertilizers and pesticides; thus, the need of the hour is to use these chemical-based products judiciously with the bio-based products (biofertilizers and biopesticides). Rather, organic production can be promoted in the selected niche or crops to satisfy the demand of the domestic export market (Mishra et al. 2013). Organic farming primarily relies on the natural soil microflora comprised of all the beneficial bacterial and fungal species including arbuscular mycorrhiza fungi (AMF). Biofertilizers and biopesticides being the fundamental constituents of organic farming enhance crop production as well as protection. Biofertilizers augment the soil fertility by making it affluent in all the essential micro- and macronutrients by the microbial nitrogen fixation, potassium (K), and phosphate solubilization, the release of phytohormones, and degradation of organic matter. Biopesticides are composed of biocontrol agents to prevent crop loss from diseases, weeds, insects, and nematodes (Abbey et al. 2019). Thus, the holistic twin approach of biopesticides and biofertilizers in organic farming would assist in the augmentation of crop yield throughout the globe with the simultaneous maintenance of soil fertility.

17.2 Need of Bio-Based Fertilizer and Pesticides

In the twenty-first century, one of the major tasks is to fulfil the food requirement of the burgeoning population on the planet with the employment of environmental and economically sound agriculture inputs (Meena et al. 2016). Besides this, the blanket use of agrochemicals is severely declining the population of beneficial microorganisms that further makes the crops more susceptible to biotic and abiotic stresses. The promiscuous utilization of agrochemicals is directly affecting the biogeochemical cycles also to the great extent due to the detrimental effects of agrochemicals on the ecosystem. Moreover, the natural reserves of phosphate (phosphate rocks) are on the verge of complete depletion; on the other side, the high energy-consuming Haber-Bosch process of nitrogen fertilizers production depends on the fossil fuels leading to the depletion of natural non-renewable resources with the aggravation of global warming (Erisman et al. 2013; Cordell and White 2014). Thus, the cost of the chemical-based fertilizers is rising dramatically with the increase in prices of petroleum-based products utilized for their production. The production of agrochemicals requires high energy input, for instance, 1.1 kWh phosphorus (P), 11.2 kWh nitrogen (N), and 1 kWh Potash are required for the production of 1 kg of fertilizer (Saritha and Prasad Tollamadugu 2019). Therefore, after being cognizant about the ruinous effects caused by the agrochemicals and their skyrocketing costs, there is an urgent need to exploit the salubrious interaction between plants, soil microflora, and the environment. There are several plant interacting soil microbes that contribute to the plant growth with the significant enhancement in soil fertility utilized as biofertilizers. At the same time, biopesticides also offer multiple advantages including the targeting of specific pests rather than affecting the whole range of pests

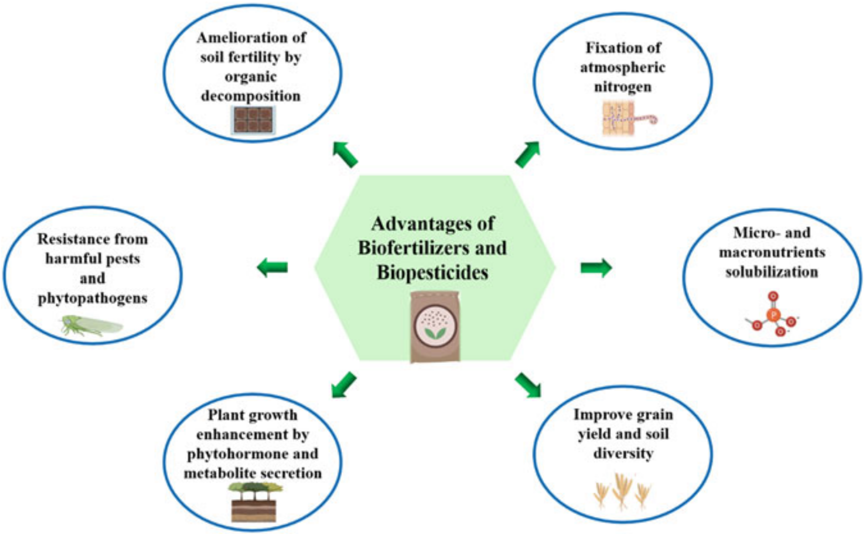

Fig. 17.1 Advantages of biofertilizers and biopesticides in agriculture

together with many birds and animals. The biopesticides are degraded more quickly and required in minimal quantity when compared to chemical-based pesticides, thereby decreasing the exposure. Thus, the biopesticide can be employed as an alternative to the chemically synthesized pesticides in the integrated pest management (IPM) programs, contributing higher crop yield and less harm to the environment (Thakore 2006). The bio-based fertilizers and pesticides formulated by the incorporation of microorganism strains or other natural substances may help in dealing with all the challenges coming in sustainable agriculture practice. The major types of biofertilizers and biopesticides with their mode of action are explained in further sections. Various advantages of biofertilizers and biopesticides are depicted in Fig. 17.1.

17.3 Biofertilizer: A Boon for Sustainable Agriculture Practice

Biofertilizers, generally mentioned as bioinoculants, are the reasonable and eco-friendly microbial preparations that increase the bio-accessibility and bioavailability of plant nutrients. The biofertilizers are prepared from the active or latent strains of microorganisms belonging to the bacterial, fungal, and algal domain. Mostly, bacterial strains are solely employed as bio-inoculants, but in some cases, the combination of bacterial species with fungi or algae has also been used to boost the microbial activity (Suyal et al. 2016). These microorganisms themselves do not serve as the source of nutrition to plants but participate in various rhizospheric interactions to convert the nutrients to plants' utilizable form. These rhizospheric interactions lead to several biochemical processes that involve the fixation of nitrogen (N), solubilization of zinc (Zn) and phosphate, and mobilization of potash, phosphate, and other micronutrients (Suhag 2016; Suyal et al. 2016; Anand et al. 2016; Kamran et al. 2017). Additionally, these microorganisms also assist in the plant growth by secretion of various phytohormones such as auxins, gibberellins, cytokinins, and abscisic acid that directly boost the plant growth (Wong et al. 2015). There are many other roles played by the bacterial species that stimulate the plant growth, viz., secretion of lyases and siderophores, production of antibiotics and low molecular weight metabolites that antagonize other plant pathogens from the colonization on roots, and confer induced systemic resistance (ISR) in plants (Kumar 2018; Gopalakrishnan et al. 2015). Thus, owing to the ability of these microorganisms to promote plant growth together with providing resistance against various stresses, they are generally regarded as plant growth-promoting microorganisms (PGPM). In particular, the fungi and bacteria possessing the potential to alleviate the plant growth are called plant growth-promoting fungi (PGPF) and plant growth-promoting rhizobacteria (PGPR), respectively. The PGPRs have the potentiality to enhance the plant's growth either by direct or indirect mechanisms. The direct secretion of phytohormones and nutrients induces the plant growth directly, whereas the symbiotic association of bacterial species with plants supports the indirect mechanism (Kenneth 2017; Kenneth et al. 2019).

Primarily, the biofertilizers comprised of microorganisms having the potential to fix nitrogen and solubilize phosphate and cellulolytic enzymes secretion. The nitrogen-fixing biofertilizers mainly include *Rhizobium*, *Azolla*, *Azotobacter*, *Cyanobacteria*, and *Azospirillum* having the ability to fix atmospheric nitrogen into the soil in plant utilizable forms. The phosphate-solubilizing biofertilizers such as *Bacillus* and *Pseudomonas* can efficiently solubilize the tricalcium phosphates (TCP) and rock phosphate by secreting various organic acids to make it readily available to the plants (Dotaniya et al. 2013, 2014). The nitrogen-fixing biofertilizers composed of *Rhizobium*, *Azospirillum*, and *Azotobacter* blanket the major portion of the biofertilizers value in the market share. Altogether, the global market value of the biofertilizers was estimated at around USD 1.0 billion in the year 2019, which is expected to evidence a compound annual growth rate (CAGR) of 12.8% between 2020 and 2027 (https://www.grandviewresearch.com/industry-analysis/biofertilizers-industry).

The history of the employment of biofertilizers in agriculture is way too long as the farming community has been continuously using biofertilizers from the generations in rural areas in the form of microbial inoculations of small-scale compost. Still, there is some kind of confusion in the farming community regarding the cost and efficacy of biofertilizers due to the lack of poor handling and storage. Biofertilizers are apparently considered as more expensive than chemical-based fertilizers due to the lack of knowledge about modern technologies that can be utilized to manufacture biofertilizers from available biowastes, short shelf life, suitable carrier material, and instability at high temperatures (Singh et al. 2016). Thus, there is an urgent need to resolve these issues to expand the utilization of biofertilizers in remote areas along with the provision of proper training about the usage and storage of these bio-based products to the farmers.

17.4 Types of Biofertilizers

In natural ecological systems, nutrients such as nitrogen, phosphorus, and sulfur are found in a bound state with the organic molecules which are not utilized directly by plants. Thus, the plants solely rely on the soil microorganism to make these growth-limiting nutrients biologically accessible to them. These soil microorganisms through various metabolic processes convert them into the inorganic forms such as nitrate, ammonium, sulfate, and phosphate and further release them into the soil (Van Der Heijden et al. 2008; Jacoby et al. 2017). Likewise, the biofertilizers composed of these essential soil PGPM can efficiently bring about the nutrient transformations that will enhance the crop productivity with the maintenance of soil diversity. The role and interactions of soil microorganisms with plants in sustainable agriculture practice have been comprehensively reviewed by many researchers worldwide (Meena et al. 2016; Li et al. 2017). At present, biofertilizers as an integral component of organic farming are the center of attraction; thus various types of biofertilizers based on their function and interaction with plants are addressed in the next subsections (Fig. 17.2).

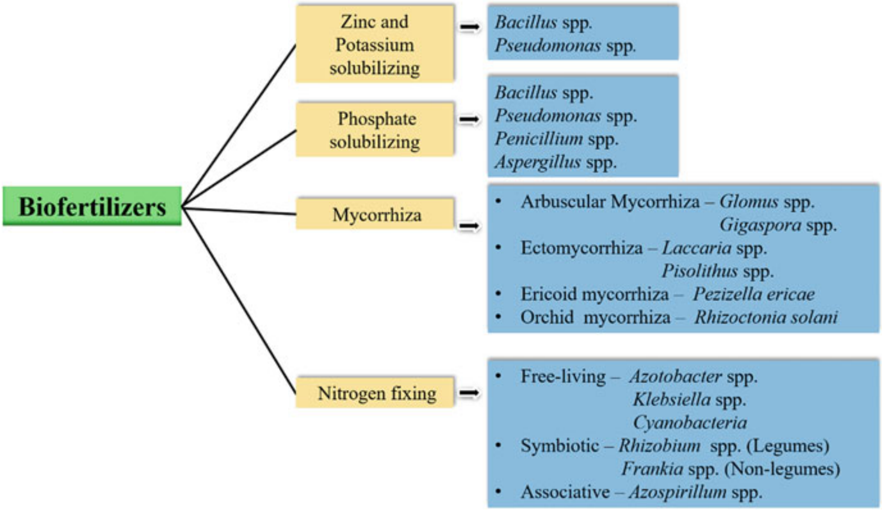

Fig. 17.2 Various types of biofertilizers employed in organic farming

17.4.1 Nitrogen-Fixing Biofertilizers

Nitrogen (N) is one of the main constituents of biomolecules (nucleic acids and proteins) and plays a vital role in the growth and development of all living beings. In plants, it serves as a pivotal element of chlorophyll, alkaloids (colchicine, nicotine, quinine, etc.), plant growth hormones, and glucosinolates. N in the gaseous form makes up approximately 78% of the total Earth's atmosphere, yet cannot be utilized directly by the plants and animals. Thus, it needs to be converted into the relevant organic form (such as ammonium or nitrate) to be utilized in the formation of biomolecules. Several soil microorganisms possess the oxygen-sensitive nitrogenase enzyme for the fixation of atmospheric N into ammonia. This process is generally known as biological N fixation. Mainly, the bacterial species that carry out the process of nitrogen fixation are either free-living (*Azotobacter* and *Azospirillum*) or found in symbiotic association with plants (*Rhizobium* and *Frankia*). *Rhizobium*, *Sinorhizobium*, and *Bradyrhizobium* make symbiotic associations with the leguminous plants and cause root nodule formation. Likewise, *Frankia* forms the root nodule in the non-leguminous actinorhizal plants (Kumar 2018). The cyanobacteria and mycorrhiza have also been reported to participate in the process of nitrogen fixation (Pereira et al. 2009; Püschel et al. 2017).

The N-fixing symbiotic bacteria, *Rhizobium*, is a member of the family *Rhizobiaceae* that can fix nitrogen in legumes at 50–100 kg ha^{-1} and also in some non-leguminous plants such as *Parasponia*. *Rhizobium* gets access in the root system of legumes after germination of seed and colonizes there to form tumor-like growth which is known as root nodules that act as the ammonia manufacturing units. The addition of *Rhizobium* as bio-inoculants in the fields can considerably upsurge the crop yield and benefit several leguminous crops such as lentil, gram, and chickpea; vegetables like sugar beet, pea, and alfalfa; and oilseeds crop including groundnut, soybean, and lentil (Baset Mia and Shamsuddin 2010; Giri and Joshi 2010). Samago et al. (2018) conducted a field experiment on common bean in low-P soil of Ethiopia to examine the effects of *Rhizobium* inoculation and phosphorus application (20 kg P ha^{-1}) on the grain yield, plant growth, and symbiotic performance. The results showed accelerated plant growth and symbiotic performances owing to *Rhizobium* inoculation and high grain yield in the P-fed plants. Similarly, Khan et al. (2018) reported that bio-inoculation of *Rhizobium* strains on three leguminous crops (chickpea, mung bean, and pigeon pea) has positively affected the plant growth, N uptake, nodulation, and leghemoglobin content. Also, the occurrence of galling and reproduction of *Meloidogyne incognita* has been reduced largely in chickpea, mung bean, and pigeon pea through the seed treatment by *Bradyrhizobium japonicum*, *Mesorhizobium ciceri*, and *Rhizobium* sp., respectively. This indicates the dual benefit of *Rhizobium* as biofertilizers by enhancing the crop yield by nitrogen uptake as well as providing protection against biotic stresses. *Azotobacter* belongs to the family *Azotobacteraceae*, which is a heterotrophic, free-living, and aerobic bacteria that colonize on the plant roots and fix around 25 kg N ha^{-1}. The production of antifungal compounds has been observed from

Azotobacter species in the rhizosphere that antagonizes growth of fungal phytopathogen, thereby increasing seeding survival rate (Mishra et al. 2013). Romero-Perdomo et al. (2017) evaluated the influence of *Azotobacter chroococcum* strains AC1 and AC10 on the cotton plant growth, and findings suggested that the co-inoculation of both the strains has reduced the supplementation of N-fertilizers by 50%. The effect of *Azotobacter* sp. and *Azospirillum* sp. on the growth of tomato plants was assessed by Reddy et al. (2018), and results revealed that inoculation of *Azotobacter* sp. and *Azospirillum* sp. with 75% dose of NPK fertilizers displayed the maximum growth in tomato plants. *Azospirillum* (*Rhodospirillaceae)* are heterotrophic and associative bacteria with the potential of 20–40 kg ha^{-1} N-fixing. *Azospirillum* is one of the extensively studied PGPR from the lab to field experiments. It is considered as the safest bacterial species to be utilized as biofertilizer owing to its non-pathogenic behavior. It holds the potential to fix N and solubilize phosphate, phytohormones, and siderophore production (Mehnaz 2015). Sahoo et al. (2014) isolated several strains of *Azospirillum* from the different rhizosphere of rice fields and assessed their effects as biofertilizer. The results revealed that *Azospirillum lipoferum* (As6) has significantly improved the nutrient content, growth, and yield of rice var. *Khandagiri* along with good N-fixing performance, phytohormone production, siderophore secretion, and iron tolerance. Mazhar et al. (2016) evaluated the salinity tolerance and biocontrol potential of the *A. lipoferum* and observed the resistance from *Aspergillus niger* and *Pseudomonas* with considerable salt-stress tolerance in wheat crop. *Azolla* (*Cyanobacteria*) is mostly utilized as green manure or compost. Similar to other N-fixing biofertilizers, it can also assist in the N-fixation as well as phytohormone production for the plant growth promotion. Razavipour et al. (2018) observed that *Azolla filiculoides* compost has notably improved the growth and yield of rice crop for two growing seasons under the water-deficient conditions. The inoculation of 5.0% of total soil has given the highest grain yield which was found to be 13.8% higher than uninoculated crops. Maswada et al. (2020) demonstrated the effect of *A. filiculoides* extract application on maize plants under nitrogen- and water-deficient conditions. The results displayed substantial increase in N uptake, plant growth, grain yield, N-utilization efficiency, and proline accumulation along with notable alleviation in oxidative damage. Additionally, the implementation of urea fertilizer has been decreased by 30% with the application of *A. filiculoides.* Thus, *Azolla* is one of the potential candidates in the development of water saving and low-input agriculture system.

17.4.2 Phosphate Solubilizing Biofertilizers

Phosphorus (P) is the highly essential element for the biosynthesis of phospholipids and nucleic acids and also the most crucial macro-element for the plants after N. It plays important role in the process of photosynthesis and respiration as it is the core component of the “molecular currency,” i.e., adenosine triphosphate (ATP). Plants utilize the P in the form of orthophosphates, i.e., $H_2PO_4^-$ and HPO_4^{2-}. P is available in soil in both organic and inorganic forms; out of which, organic form is usually found in decayed organic matter and humus which constitutes a significant reservoir (~30–50%) of P in soil. Most of the P content found in soil is usually fixed, i.e., forms chemical compounds with hydrated oxides or hydroxide of other elements, therefore becoming unavailable for plants. A large part of the fixed P in soil is found due to the application of chemical inorganic phosphate fertilizers which are partly utilized by the plants, and the remaining get immobilized or fixed. There are several microorganisms found in the soil and rhizosphere possessing the ability to solubilize the phosphates of various elements including calcium (Ca), iron (Fe), and aluminum (Al) found in soil. These microorganisms formulate the P mineralizing and solubilizing biofertilizers. They can be aerobic or anaerobic, but in submerged soil, aerobic microbes are more prevalent.

P-fixation and precipitation are highly influenced by soil pH and type. The P-fixation is found to be higher in the acidic or calcareous soil conditions, which can be alleviated by the proper adjustment of soil pH to make phosphorus biologically available to plants (Mahdi et al. 2012). In acidic soils, phosphorus fixation occurs with the hydroxides or oxides of Al and Fe, whereas in alkaline soil conditions, phosphorus fixation occurs by calcium. Phosphate solubilizing biofertilizers secret the organic and inorganic acids which act on inorganic phosphorus and chelate cations (Ca, Fe, Al) through their acidic hydroxyl and carboxyl groups which further decrease pH in alkaline soil. Phosphate solubilizing biofertilizers secret the organic and inorganic acids which act on inorganic phosphorus and chelate cations (Ca, Fe, Al) through their acidic hydroxyl and carboxyl groups. For the solubilization of mineral phosphates, tri-/di-carboxylic acids have known to be more helpful when compared to monobasic and aromatic acids (Mahdi et al. 2012). The solubilization of organic phosphates in the soil is known as mineralization, which can be achieved by the action of phosphatases derived from soil microorganisms. These phosphatases catalyze the conversion of organic phosphate into inorganic form by utilizing them as a substrate. The most widely used microorganisms as phosphate solubilizing biofertilizers are *Bacillus* spp. (Sharma et al. 2007), *Pseudomonas* spp. (Oteino et al. 2015), *Xanthomonas* spp., *Aspergillus* spp. (Mittal et al. 2008), and *Penicillium* spp. (Reyes et al. 2002; Pradhan and Sukla 2006). Sharma et al. (2007) performed the inoculation of chickpea seeds with *Bacillus megaterium* and *Pseudomonas fluorescens* as phosphate-solubilizing fertilizers with the solubilization efficiency of 128.57 and 200.00, respectively. The findings suggested increased seed germination efficiency, seedling length, and yield; and *P. fluorescens* was found to be more effective, whereas co-inoculation showed more seedling length when compared to single inoculation. The phosphate-solubilizing fertilizer (*Aspergillus niger*) has been reported to enhance the height of the plant, leaf length/width, size of fruit, and number of fruits per plant in okra and bottle guard when utilized together with N-fixing *Azotobacter* sp. (SR-4) (Din et al. 2019). Similarly, the N-fixing *Rhizobium meliloti* and *Klebsiella pneumonia* as phosphate solubilizer as biofertilizers decreased the mortality rate in alfalfa seedlings and increased the root length, shoot height, leaf area, root volume, number of leaves per plant, biomass, and uptake of P in two alfalfa varieties (Li et al. 2013). Oteino et al. (2015) conducted a study on the utilization of endophytic bacteria *Pseudomonas fluorescens* strains as phosphate-solubilizing biofertilizers on pea plants. The results revealed that three strains of *P. fluorescens* L111, L228, and L321 have proficiently solubilized phosphate (400–1300 mg L^{-1}), secreted gluconic acid, and enhanced plant growth. The *P. fluorescens* L321 boosted the plant growth even in the phosphate-limiting conditions, thus considered as the most effective out of all the strains. The studies clear the ability of phosphate-solubilizing biofertilizer in the enhancement of plant growth and soil fertility.

17.4.3 Potassium-Solubilizing Biofertilizers

Potassium (K) is considered as the third most essential nutrient for the plants after N and P. It participates in the opening and closing of stomata, which leads to the regulation of osmotic balance in the plant (Abbey et al. 2019). K-deficient plants possess less developed root system, slow growth, small seeds, and lower product yields (Teotia et al. 2016). In soil, K exists in the various forms which include mineral K, non-exchangeable K, exchangeable K, and ionic K (solution or dissolved form). The K is abundantly present in the soil, yet 1–2% of total K is utilized by the plants because the remaining K cannot be used by the plants as it occurs in silicate mineral form (mica and K feldspar) (Zhang and Kong 2014). The organic acid-producing microorganisms can be utilized as biofertilizers to increase the solubilization of K in soil. The organic acids can readily solubilize K by making a complex with calcium ions or by providing protons (Shanware et al. 2014). *Bacillus* spp. (*B. circulans*, *B. edaphicus*, *B. megaterium*, *B. mucilaginosus*) have been studied extensively for the solubilization of K. Besides, several other bacterial and fungal species have also been reported to have K solubilization ability including *Arthrobacter* sp., *Pseudomonas putida*, *Paenibacillus* sp., and *Aspergillus* spp. (Teotia et al. 2016; Verma et al. 2017). Singh et al. (2010) demonstrated the mobilization of K from the mica waste (MW) by *Bacillus mucilaginous* when inoculated with maize and wheat, whereas the *Rhizobium* spp. and *Azotobacter chroococcum* also displayed K solubilization potential. Likewise, *Bacillus pseudomycoides* isolated from the rhizosphere of tea plants solubilized 33.32 ± 2.40 μg mL^{-1} of K from the broth amended with MW after 7 days incubation, while in soil microcosm, 47.0 ± 7.1 μg kg^{-1} of K was solubilized after 105 days incubation in laboratory conditions (Pramanik et al. 2019). The studies indicate the tremendous potential of these microbial strains to be employed as K-solubilizing biofertilizers.

17.4.4 Zinc-Solubilizing Biofertilizers

Zinc (Zn) is recognized as one of the most important micronutrients for both eukaryotic and prokaryotic organisms as it acts as a cofactor and activator in many enzymes. It participates in protein synthesis, seed development, and growth hormone production (Abbey et al. 2019). The 96–99% of exogenously supplied soluble Zn as fertilizer to the plants convert into the unavailable form and get fixed in the soil. Various parameters of soil such as high pH, organic matter, high $CaCO_3$ content, copper, and phosphate level can fix the soluble Zn into the soil. The solubilization of Zn in the soil can be achieved through the utilization of organic acid-producing microorganisms found in soil. The lowering of soil pH by the release of organic acids such as gluconic acid, glycolic acid, acetic acid, lactic acid, etc. sequester the cations leading to the acidic rhizospheric environment that would help in Zn solubilization. Additionally, the anions can solubilize Zn by its chelation and convert it into a plant usable form, i.e., Zn^{+2} (Kumar 2018). Several microorganisms have proved their potential in Zn solubilization, viz., *Bacillus* sp., *Pseudomonas* sp., *Aspergillus* sp., and *Klebsiella* sp. (Khande et al. 2017; Gontia-Mishra et al. 2017). Four bacterial species (*Pseudomonas aeruginosa*, *Ralstonia pickettii*, *Burkholderia cepacia*, and *Klebsiella pneumoniae*) isolated from the rhizosphere were analyzed for their ability to solubilize the Zn from ZnO and $ZnCO_3$ present in the medium. The results displayed that Zn solubilization promoted the growth in rice seedling and other cereals. Moreover, Zn-solubilizing bacterial species possessed several other plant growth-promoting characteristics also like P and K solubilization, exopolysaccharide production, and 1-aminocyclopropane-1-carboxylic acid (ACC) utilization Gontia-Mishra et al. 2017).

17.4.5 Mycorrhiza Biofertilizers

Mycorrhiza, commonly recognized as fungus root, is the symbiotic association between roots of plant and soil fungal mycelia. In this symbiotic association, the host plant gets benefited with the easy accessibility of growth-limiting nutrients with the help of fine fungal hyphae, and in turn, fungi fulfil its carbon requirements from the plant (Mishra et al. 2013). The AMF possesses a special structure known as arbuscules for the efficient transfer of nutrients from fungus to the root system and vesicles for the storage of P (Dhir 2017). Various types of mycorrhizal associations have been studied so far, namely, ectomycorrhiza, endomycorrhiza (arbuscular mycorrhiza, AMF), ectendomycorrhiza, ericoid mycorrhiza, orchid mycorrhiza, arbutoid mycorrhiza, and monotropoid mycorrhiza. The AMF is highly important as it is prominently found in approximately 85% of terrestrial plant families. The hyphae of AMF reach beyond the nutrition depletion zone in search of the high amount of mineral nutrients for the plant. Thus, AMF benefits the plant by enhancing P content, tolerance to various biotic and abiotic stresses, micronutrients and water uptake, the survival rate of seedling, and resistance against pest and other phytopathogens (Kumar 2018). The effect of four AMF species (*Gigaspora margarita* P18, *Scutellospora heterogama* P29, *Acaulospora longula* P20, and *Funneliformis mossease* P07) isolated from different soils sampled from various fields was investigated on the growth promotion and drought stress tolerance ability of various crops (sorghum, leek, carrot, and red pepper). The AMF conferred the positive effect on the growth and drought-tolerant ability of sorghum and carrot, whereas comparatively lesser growth was observed in red pepper and leek (Kim et al. 2017). Likewise, Oyewole et al. (2017) examined the influence of *Gigaspora gigantea* and *Glomus deserticola* on the growth drought tolerance potential of cowpea. The *G. deserticola* affected the water stress tolerance ability and product yield positively, while the combination of *G. deserticola* and *G. gigantea* has provided resistance against charcoal rot disease of cowpea caused by *Macrophomina phaseolina.* The role of biofertilizers in the amelioration of soil fertility and plant growth promotion has been comprehensively advocated with the implications in various improvements; thus, the contribution of biopesticides as a part of IPM is discussed in further sections.

17.5 Biopesticides

Biopesticides have emerged as a competent alternative for chemically synthesized pesticides. They offer multiple benefits to the crops as compared to chemical pesticides such as environmental safety, target specificity, biodegradability, efficacy, and cost-effectivity (Gupta and Dikshit 2010). Even the continuous use of biopesticides on crops poses no detrimental impacts on the agroecosystems. Biopesticides possess a wide range of microbes and microbes-derived biochemical substances to confer resistance against pests including bacteria, fungi, nematodes, and insects. Biopesticides can be composed of metabolites derived from microorganisms, phytochemicals, or any other microbial by-product that can control pests in an eco-friendly manner through various non-toxic mechanisms. The formulations of microbes containing biopesticides can either be solid or liquid. Solid formulations consist of solid carriers including clay, lignite, talc, etc. and give high crop yield, whereas the liquid formulations are composed of various solvents, namely, water, organic acids, or oil. The liquid formulations have several advantages over solid, as they have longer shelf life, high efficacy and purity, and easy application and handling (Dhir 2017). Broadly, the biopesticides contain the microbial pathogen or natural substances malicious to the target pest, including bioinsecticides, biofungicides, and bioherbicides. They are extensively used in the regions where niche markets, pesticide resistance, and environmental concerns restrict the employment of chemical pesticides. Additionally, biopesticides also serve in the maintenance of beneficial native microbes diversity and insects population owing to the target specificity and non-hazardous implications of biopesticides. Employment of biopesticides in agriculture also aids the farming community to satisfy the demands of enlightened consumers regarding their health and food safety(Abbey et al. 2019).

Global production of biopesticides is approximately 3000 tons per year which is accelerating every year at a rapid pace. In 2014, the US Environment Protection Agency (EPA) has registered over 1320 biopesticides products together with more than 430 active ingredients for biopesticides production (Mehrotra et al. 2017). Asia covers just 5% of total biopesticides sold in the market globally, whereas the US market holds first position in the sale of biopesticides with 200 products. Notwithstanding the environmental safety and low toxicity, the implementation of biopesticides is restricted due to several limitations like short shelf life, high costs, and scarcity. Therefore, it becomes difficult for small and marginal farmers to afford the additional expense of biopesticides. For the growth of the biopesticides market, the pressing priority is to increase research and development along with the ease in procedures for product registration and licensing. Furthermore, regular awareness programs should be organized to make the farmers and growers aware of the leading advantages of biopesticides in agriculture (Mishra et al. 2015).

17.6 Categories of Biopesticides

Biopesticides are broadly categorized into three categories depending on the active biocontrol agent or substance present as microbial pesticides, plant-incorporated protectants (PIPs), and biochemical pesticides. The specific roles of these biopesticides are elucidated in the following subsections.

17.6.1 Microbial Pesticides

The exorbitant use of chemical pesticides in agriculture has led to the development of resistance in many pests leading to the generation of new strains of pests. This phenomenon of resistance development in pest has made the researchers worried, which led to the foundation of biopesticides development (Nawaz et al. 2016). Besides this, the occurrence of acute or chronic poisoning in the developing countries further necessitated the need for bio-alternatives to control the pests. Microbial pesticides are formulated with potent microorganisms (bacteria, viruses, algae, fungi, and protozoans) as active biocontrol ingredients. The microorganisms employed for the construction of microbial pesticides are highly specific to the target pest. Microbial pesticides control the pests by making them diseased through the secretion of specific toxins. Majorly, the toxins secreted by these microorganisms are peptides that are distinct to each other in terms of specificity, toxicity, and chemical structure (Abbey et al. 2019).

The most extensively studied microbial pesticide is the insecticidal bacterium, *Bacillus thuringiensis* (*Bt*). This has been implied for the protection of crops from

Table 17.1 List of various microbial pesticides employed for development of pest-resistant plants

Microbial pesticide	Target pest	Crop improved	References
Bacillus thuringiensis	*Helicoverpa armigera*	Alfalfa	Sharma et al. (2011)
Metarhizium anisopliae *Beauveria bassiana*	*Bemisia tabaci* *Frankliniella occidentalis* *Bactericera cockerelli*	Tomato	Rios-Velasco et al. (2014)
Metarhizium anisopliae *Paecilomyces fumosoroseus*	*Spodoptera exigua*	Chinese cabbage	Han et al. (2014)
Bacillus thuringiensis	*Diabrotica virgifera virgifera*	Maize	Jakka et al. (2016)
Bacillus thuringiensis	*Hyphantria cunea* *Lymantria dispar*	Poplar	Wu et al. (2019)
Metarhizium anisopliae	*Nilaparvata lugens* *Sogatella furcifera*	Rice	Tang et al. (2019)
Metarhizium robertsii *Beauveria bassiana*	*Tetranychus urticae*	Bean	Canassa et al. (2019)
Metarhizium anisopliae	*Frankliniella occidentalis*	Eggplant	Li et al. (2021)

black flies, mosquitoes, and moths (caterpillars/larvae). The enormous amount of research has been conducted on the *Bt*, and it has become the first commercially employed biopesticide across the world. The protein crystals (δ-endotoxin) produced by *Bt* during spore formation are applied to plant foliage. The ingestion of these protein crystals or endotoxin by insects while feeding on plant causes lysis of their gut cells which result in the death of insect (Dhir 2017). *Bacillus subtilis* has also been reported to protect plants against phytopathogens using its antibiosis activity (Romero et al. 2007). Fungi also have the potential to protect the crops against multiple insects and act as a mycoinsecticide agent. Fungi intrude in the insect body by penetrating the cuticle and secret mycotoxins after entering into the hemolymph, thus employed widely to control the insects having piercing mouthparts like whiteflies and aphids. Many fungal species including *Metarhizium anisopliae* (Kern et al. 2010), *Beauveria bassiana* (Jia et al. 2010), and *Paecilomyces fumosoroseus* (Lopez et al. 2014) have efficiently proved their capability to control pests for sustainable agriculture. Several bioinsecticides have been developed using entomopathogenic baculoviruses. Baculoviruses encode many enzymes and proteins that improve its potency to infect and replicate in the host's body. The virus kills the insect by ingestion of virus applied plants that further takeovers the whole metabolic machinery of the insect for its replication and transmission (Hubbard et al. 2014). Baculoviruses hold high specificity toward their hosts and mostly infect insects and a few arthropods. Baculoviruses are categorized into two main genera, namely, *Granulovirus* (GV) and *nucleopolyhedrovirus* (NPV). Interestingly, approximately 13 NPV virus-based microbial insecticides have been registered throughout the world. Various microbial pesticides that helped in the development of pest-resistant plants are enlisted in Table 17.1.

17.6.2 Plant-Incorporated Protectants (PIPs)

PIPs are the substances produced by the genetically engineered plants having toxin encoding genes incorporated in their genome, for instance, the introduction of a gene encoding for *Bt* insecticidal protein or δ-endotoxin into the plant genome. The plant will produce the insecticidal toxin for its protection against various insects. The *Bt* toxin produced by plants gets active in the alkaline environment of the insect's gut. Vaughn et al. (2005) developed corn rootworm-resistant transgenic maize varieties by the introduction of *Cry3Bb1* gene in maize genome. Likewise, *Helicoverpa armigera*- and *Phthorimaea operculella*-resistant transgenic tomato lines were developed through the incorporation of *Cry2Ab* gene via *Agrobacterium*-mediated transformation method (Saker et al. 2011). Siddiqui et al. (2019) conducted a study to develop a double cry gene (*Cry1Ac* + *Cry2Ab*) incorporated cotton plant transgenic lines. The results of the insect assay revealed that these transgenic cotton lines showed 93% mortality rate against armyworm (*Spodoptera litura*).

17.6.3 Biochemical Pesticides

Biochemical pesticides (sometimes called as semiochemical) are composed of naturally occurring substances derived from plants, animals, or insects. This class of biopesticides control pests through non-toxic mechanisms and also obstruct the mating and population growth. For instance, the production of secondary metabolites from plants prevents the consumption of plants by herbivores. Pyrethrin, a secondary metabolite secreted by *Chrysanthemum cinerariaefolium*, acts as a potent insecticidal compound (Silvério et al. 2009). Another most common source of biochemical insecticides is neem (*Azadirachta indica*) oil (Schmutterer 1990). It possesses two organic compounds, namely, salannin and azadirachtin, highly efficacious to kill insects. Azadirachtin has the potential to kill the insect by making it incapable to undergo molting to move in the next life stage. The insect-ingested azadirachtin-treated plants die within a period of 24 h. Liang et al. (2003) demonstrated the insecticidal potential of three commercial neem-based insecticidal preparations, namely, Agroneem, Neemix, and Ecozin, against diamondback moth (*Plutella xylostella* L.). The findings revealed that all three neem-based insecticides exhibited antifeedant effect against the *P. xylostella* and also significantly reduced the size of larvae. The antifeedant and inhibitory effect of neem limonoids (azadirachtin, deacetylnimbin, salannin, 17-hydroxyazadiradione, deacetylgedunin, and gedunin) was assessed against the rice leafroller (*Cnaphalocrocis medinalis*). Azadirachtin has showed the better resistance as compared to other limonoids (Nathan et al. 2005).

17.7 Conclusion

This is the modern era of biotechnology that demands sustainable agriculture practice as the indiscriminate employment of agrochemicals for crop production not only imparting deleterious effects on the environment and human health but also depleting the highly valuable natural non-renewable resources. The depletion of non-renewable resources may lead to a world-food emergency in the next few decades. Therefore, the new vistas of sustainable agriculture need to be explored to develop agriculture-inputs judicious in terms of environment, human health, and cost. Additionally, the burgeoning demand for healthier food across the world has ignited the interest of the farming and research community toward novel organic farming strategies. Thus, the requirement for biofertilizers and biopesticides has also been increased through all these years. These bioproducts serve as commendable alternatives for the agrochemicals with multiple advantages; still meeting the food requirement without agrochemicals is not viable. This is due to some of the demerits of bioproducts such as lack of profiling and narrow target range in biopesticides, selection of appropriate microbial strain for inoculation, high-temperature instability, and shorter life span of biofertilizers due to poor handling techniques. The manufacturing and development of agricultural bioproducts need more attention to drive their journey from the lab to commercial scale. Molecular techniques can aid in the development of biopesticides with a broad spectrum of targets and high activity. For the extension of bioproducts utilization at a wider scale, more research and investment need to be done together with the organization of various seminars and training workshops covering the proper handling, storage, and application strategies of bioproducts for small and marginal farmers.

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