Chapter 10
Microbial Bioformulations: Present and Future Aspects

Usha Rani and Vivek Kumar

Contents

10.1 Introduction

One of the hardest tasks these days is to employ sustainable agricultural practices. Moreover, agricultural practices around the globe are not uniform, but usage of chemical pesticides and fertilizers is common. Around 890 man-made chemically prepared various chemicals are certified that can be used as pesticides and insecticides (Stenersen 2004). These chemicals play a crucial role in improving the crop yield and inhibiting diseases, but they are also leaving their harmful effect on environment (Fenske and Day 2005; Colt et al. 2007). The condition in developing countries is very bad; despite the fact that the usage of agrochemicals in these countries is only 20%, they encounter about 99% of mortality rate due to pesticide poisoning (Kesavachandran et al. 2009). Chief victims are farmers due to high exposure and lack of awareness. About 20,000 workers die because of exposure to pesticides every

U. Rani · V. Kumar (✉)
Himalayan School of Biosciences, Swami Rama Himalayan University, Dehradun, Uttarakhand, India

R. Prasad et al. (eds.), *Nanobiotechnology in Bioformulations*, Nanotechnology in the Life Sciences, https://doi.org/10.1007/978-3-030-17061-5_10

year (Pimentel et al. 1992). According to the WHO, majority of the reports show that pesticides used for agricultural practices have very malignant influence on human well-being; short-term effects include headaches, nausea and vomiting, rashes, respiratory failure, coma, shock, etc. (Moses et al. 1993), whereas long-term effects include reproductive problems, cancer, and neurological disorders, and in serious cases it can cause death (Sanborn et al. 2007). Further, wildlife, aquatic ecosystems, and environment also get disturbed (Berny 2007). Continuous usage of pesticides drastically influences the microbial systems present in soil, and it kills large diversity of microbial population which is beneficial for the agriculture or crop production (Dorigo et al. 2009). Different types of pesticides have different effect on microbial populations and greatly influence the microbial diversity (Johnsen et al. 2001; Spyrou et al. 2009). Chemically synthesized fertilizers are another important factor on which the majority of our agriculture depends. Different studies were conducted to determine the long-term effects of these fertilizers on fertility of soil, and reports show that regular usage can elevate the strength of total nitrogen, organic matter, and different nutrients in soil as compared to the primary values present at the start of experiment (Liang et al. 2013; Mitchell et al. 1991; Mandal et al. 2007). But quality and productivity of soil is gradually deteriorating due to excessive usage of chemical fertilizers. They also influence the microbial diversity and their functions (Nakhro and Dkhar 2010). Formulations based on microbes are known as "bioformulations." In other words, formulations which constitute of several valuable strains of microbes, which are immobilized or trapped on an inert carrier material, that can be employed to enhance plant growth and inhibit plant pathogens and can increase fertility of soil are known as bioformulations (Mendes et al. 2011). Bioformulations are found to be more effective than synthetic chemicals because formulations synthesized by a single microbe can interact with plant pathogens and can have a role in plant growth promotion and disease inhibition (Arora et al. 2010). The abiotic substrates that have the ability to provide protective environment to cells and can deliver cells viably under proper physiological environment are used as carrier molecules. Various types of substrate can be employed as carriers such as inert substances (perlite, vermiculite, polymers), some liquids, and soils (clays, peat, coal) (Bashan et al. 2014). Majority of the studies executed emphasize on the (i) development of better carrier molecules; (ii) search for microbes which can enhance crop yield; and (iii) enhancement of metabolic state and potential of the cells, so that they can be used as intercellular storage devices and can survive within carrier molecules (Kadouri et al. 2005). Bioformulations have to go through various stressful conditions during storage and production, where microbes have to survive through different situations like desiccation, hot conditions, etc. Microbes should retain high survival rates and sustain their capabilities to enhance plant development for extended durations. Various strategies are used by microbes for their survival like formation and aggregation of polyhydroxyalkanoates (PHA) or osmolytes. Higher level of tolerance toward desiccation is shown by microbes which are osmoadapted and osmolytes such as glycine betaine or trehalose are aggregated by them, in comparison to the cells which are non-osmoadapted (Bonaterra et al. 2005). Those cells which have higher PHA levels have more survival potential than those cells which have lower PHA levels; this is due to the fact that PHA imparts caliber to the cells so that they can withstand against the unfavorable physical and chemical strains (Morel et al. 2012). The most remarkable microbial-plant synergism is seen in the diazotrophic microbial relationship with plants. Diazotrophs may be symbiotic or free-living microbes which have potential to fix as well as reduce atmospheric nitrogen into ammonia; some examples of diazotrophs include rhizobia, *Azotobacter*, *Gluconacetobacter diazotrophicus*, *Azospirillum*, and *Azoarcus*. Certain phytohormones, ACC deaminase, phosphate-solubilizing molecules, iron-sequestering siderophores, and other molecules are produced by some plant growth-promoting bacteria (PGPB) and diazotrophs. *Bacillus* and *Pseudomonas* come under non-diazotrophic, plant growth-promoting bacteria (Morel and Castro-Sowinski 2013). The most commonly studied symbiotic relationship includes legume-rhizobia association for agricultural improvement and productivity enhancement. Such type of associations provides enough evidence that unification of different valuable microbes, exhibiting distinct routes of plant growth enhancement, has cumulative and synergic influence on plant development and crop yield (Morel et al. 2012). Several reports also suggest that combo of secondary metabolites produced by plants with bioformulations may amplify the agricultural productivity. However, nature-friendly bioformulations are not so popular in agro-market because of some limitations associated with them (Morel et al. 2015). The constraints include sustenance of microbial biota and vigor, unpredictable field performance, inconsistency in quality, and inadequate shelf life. There are some queries which are yet to be answered so as to gain trust of consumers and to make agricultural practices chemical free (Arora et al. 2010). To answer the questions, it is essential to ascertain the work done in the previous reports and also to know the idea in which mainstream research is going so as to determine the future aspects for the development of superior bioformulations. This chapter deals with the current and future aspects of bioformulations.

10.2 Current Situation of Bioformulations

For the elimination of plant pathogens, microbial-based formulations are being utilized all around the globe, but the supportive information about its usage all over the world is very limited (Leggett et al. 2011; Naderifar and Daneshian 2012). One of the major reasons is difference in terminology. Majority of the developing countries use the term "biofertilizers," whereas in developed countries the term "bioinoculant" for crop yield and improvement is used, but in both of the cases either compounds are isolated from living organisms or whole organism is employed for the enhancement in nutrient uptake by plants so as to improve crop yield and soil quality (Vessey 2003; Chen et al. 2006; Prasad et al. 2018). Many producers (farmers) around the globe regularly employ biofertilizers and biopesticides into their different types of crops. The most advanced and prevalent market for formulations is European biofertilizer market as compared to all other domains, and growth from $2566.4 million in 2012 to $4582.2 million was observed in 2017, at an annual growth rate of 12.3% from 2012 to 2017 (PRWEB 2014). In 2012, biofertilizer market was highest in North America and is expected to develop at the rate of 14.4%

in the duration of 2013–2018 (Micro Market Monitor 2015). China is the chief grower of wheat and rice along with cabbage and onions as well as promotes the use of biofertilizers (Grand View Research 2015). In India, there are around 151 biofertilizer manufacturing units which are run by government and nongovernment agencies (Mahajan and Gupta 2009). Mainly nitrogen-fixing biofertilizers were used in maximum as compared to all other biofertilizers, and in 2012 their worldwide demand increased over 78% (Agro news 2014). In controlling plant diseases, *Bacillus thuringiensis* (BT)-based biopesticides are more popular and constitute for 95% of the overall microorganisms employed (Bravo et al. 2011). Around 322 BT products generate a revenue of $210 million annually (CAB International Centre 2010). Usage of fungal and non-BT biopesticides is also growing. Various agencies have carried out market research survey, but outcomes of these kinds of surveys are not very reliable and are questionable. This is because criteria employed in market research survey may deviate since many firms and agro-based industries involve subcategories such as biochemicals, plant-induced protectants (PIPs), microbes, plant growth regulators, pheromones, insect growth regulators, and essential oil in the name "biopesticide," while others use only the products which are microbial in origin (Gelernter 2007). Around $672 million was biopesticide turnover in 2005 (description of category was not included) (Thakore 2006), and worldwide market of biopesticide was about $280 million in 2007 (for true microbial agents) (Harwood et al. 2007). CPL (2006) and BCC (2010) are business consultancies which are vigorously conducting direct market survey and generating a reliable data, and their reports show that biopesticide market is enhancing at a rate of 10% every year, globally. Biopesticide market was expected to exceed by $2.5 billion by 2015, via global industry analysis 2015. Other research surveys conducted by BCC on biopesticide suggested that total sale of biopesticide in 2008 was $1.2 billion and in 2009 it was $ 1.6 billion. And it was expected to increase in 2014 to around $3.3 billion and in 2017 around $10 billion (Marrone 2007). Region-wise research reports highlight that the United States is the largest region of biopesticide globally, while Europe is the fast-growing regional market for biopesticide and represents an average annual growth rate of 15.0%. Asia Pacific is also an emerging market for biopesticides, where sales were expected to be around $362 million in 2012. Latin America has shown very little increase as compared to other regions. In 2005, market was about $70 million, and in 2010 it reached only $88 million, with an average annual growth rate of 5.0% (Industrial Equipment News 2011). Table 10.1 shows the types of microbes, main crops, and areas in world utilizing microbes as bioinoculants/bioformulations.

10.3 Consortia- or Inoculant-Based Bioformulations

Majority of the bioformulations available are mostly composed of single strain or mixed cultures or are in co-inoculations with other microbes. Use of such co-inoculations helps in overall development and plant growth promotion. When mycorrhiza co-inoculated with rhizobia, it displayed enhanced performance with legumes. This association helps to enhance the nutritional value of most nodulated plants and

Table 10.1 Types of crop, microbes, and agricultural market of bioinoculants

Market by type	Market by mode of application	Market by microbial type	Market by type of crop	Market by type of geography
Biocontrol agents	Seed inoculant	Bacteria: rhizobacteria N_2 fixing P-solubilizing Cyanobacteria Others	Cereals and grains	North America: USA, Canada, Mexico, other North American countries
Plant resistance stimulants	Soil inoculant	Fungi: *Trichoderma* sp., AM fungi *Aspergillus*	Oil seed and pulses	Europe: Germany, France, Spain, Italy, Denmark, other European countries
Plant growth-promoting microbes	Foliar spray	Others: Azolla-Anabaena	Fruits and vegetables	Asia Pacific: Australia, China India, Japan, other countries
Plant stress manager	Other inoculants		Other crop types	South America: Brazil, Chile, Argentina. LAMEA countries (Latin America, Middle East, and African countries)

also raises the tolerance toward drought and other osmotic stress in pigeon pea (Bhattacharjee and Sharma 2012), lucerne (Ardakani et al. 2009), soybean (Gao et al. 2012), broad bean (Jia et al. 2004), and chickpea (Tavasolee et al. 2011). Several reports also suggest that plant growth is stimulated after the employment of nodule-forming bacteria with Phosphate solubilizing bacteria (PSB) in leguminous plants (Messele and Pant 2012). Currently, several studies have been conducted related to consortia formulation development by different researchers and patents have also been filed (Paikray and Malik 2010). Maiyappan et al. (2010) conducted a study in which a bioformulation consortium was prepared (as a wettable powder) which involved nine strains of the following genera—*Frauteria*, *Bacillus*, *Azotobacter*, and *Streptomyces*, and this formulation was found to be useful for black gram. Similarly, consortium bioformulation was prepared using *Burkholderia* species MSSP plus three other plant growth-promoting bacteria and was examined for the development of *Cajanus cajan*, by employing different carriers like sawdust, rock phosphate, bagasse, wheat bran, cocoa peat, charcoal, rice husk, and paneer whey, and this consortium was found to be effective in enhancement of pigeon plant growth, when used as a formulation (Pandey and Maheshwari 2007). Studies conducted by Tajini et al. (2012) demonstrated that in bean plants, when arbuscular mycorrhizal (AM) fungi and rhizobia are inoculated in combination, they help in enhancing uptake of nitrogen and potassium in plants as compared to single inoculation. Further, according to some researchers, the consortia can be prepared using *Azotobacter*, microalgae, and cyanobacteria, which can be employed as biofertilizer and bio-stimulator (Zayadan et al. 2014). Figure 10.1 shows the basic comparison of plant growth promoting rhizobacteria (PGPR) and bioformulations used in agroecosystem.

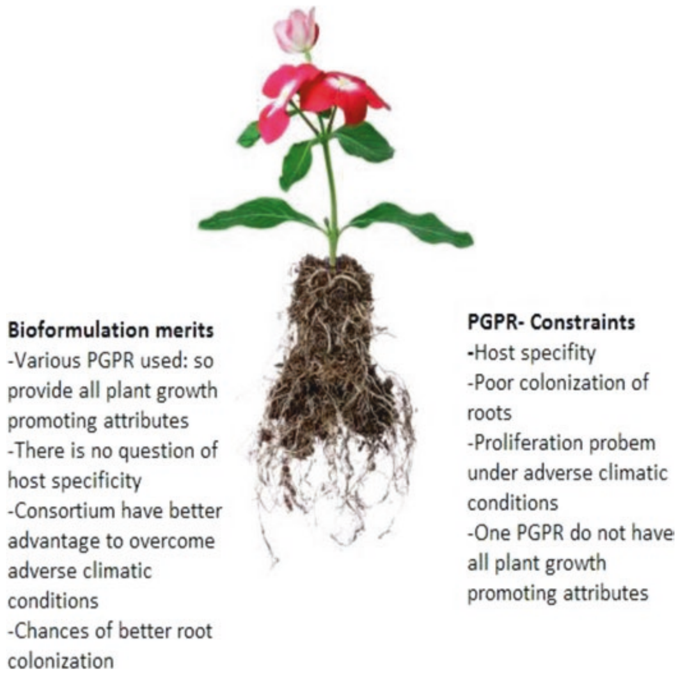

Fig. 10.1 Some comparisons of bioformulations with PGPR under agro-climatic conditions

10.3.1 Inoculums Production Approaches

10.3.1.1 Inoculants Based on Carriers

A carrier is usually locally available and reasonably affordable material that has efficient water-holding capacity and is competent enough to slowly liberate its viable cells into soil. Agro-industrial residues, peat, compost, vermiculture, charcoal mixed with soil, bentonite, and perlite are some of the commonly available and economically friendly organic materials that are utilized for making microbial inoculants. After a suitable carrier is selected, it is sterilized and amalgamated with definite microbes such as phosphate-solubilizing or nitrogen-fixing microbes under sterile environment. Such carrier-based bioformulations can be stored only for 3–4 months and have high cell density. When stored at room temperature, cell density decreases at a very high rate (Trivedi et al. 2005).

10.3.1.2 Inoculants Based on Clays

The most widely utilized formulation in agricultural domain is “clay.” It may be employed in a number of forms such as powder, suspension, or granules. Use of clays can increase the shelf life of microbial strains as they have large pore size and surface area. It offers suitable conditions for microbes to flourish (Smith 1992).

10.3.1.3 Liquid Formulations

Liquid bioformulations are made by using specific microbes which are prepared in a mineral-based medium, broth-based medium, or organic oil-based suspension (Schisler et al. 2004). When these liquid formulations are employed, the microbial inoculants come in direct contact with soil or seeds and perform their action; however, protective environment for microbial strains is absent. This kind of formulation is not suitable for long-term storage and is highly susceptible to contamination during storage. Suitable environmental conditions are required for maintenance so that microbial strains do not lose their viability and efficacy (Brar et al. 2006).

10.3.1.4 Encapsulation

In bio-encapsulation procedure, active strains are incorporated into solid or liquid matrix, where materials like polystyrene, alginate, agarose, polyacrylamides, agar-agar, polyurethane, carrageenan, synthetic polymers, etc. are utilized as matrix (John et al. 2011). The stabilization is done by chemical polymerization. It can be stored as long as 5 years.

10.3.1.5 Use of Biofilms

Biofilms are based on microbial cell aggregates. Biofilm involves four stages in its development which are (a) primary adherence, (b) irrevocable immobilization by generation of exo-polysaccharide, (c) prematuration stage, and (d) maturation stage. Biofilms prepared by employing fungal and bacterial strains have been found adequate (Seneviratne et al. 2008).

10.3.2 Outcome of Inoculants/Formulations

10.3.2.1 Mycorrhizal Fungi Inoculants

Arbuscular mycorrhizal fungi belonging to phylum *Glomeromycota* have potential to form symbiotic relationship with majority of the land plants (Schubler et al. 2001; Prasad et al. 2017a). They use their host as a carbon source and help the host plant by promoting its growth by providing nutrients, water, and minerals. AMF influence the soil microbes and form mycorrhizospheric zone in the soil (Linderman 1988). The AMF present in mycorrhizosphere may have positive (Albertsen et al. 2006) or negative (Cavagnaro et al. 2006) or no effects (Olsson et al. 1996) at all on the growth of microbes or microbial biomass. Several studies show that certain bacterial species behave differently in the vicinity of specific AMF; this suggests that bacteria and AMF might have high degree of specificity between them (Artursson et al. 2006). Therefore, AMF associated with specific bacteria may prove to be useful for plant development by providing essential nutrients, enhancing branching of roots (Barea 1997). AMF also provide protective benefits by inhibiting the proliferating pathogens by forming the bacterial populations which limits the invasion of pathogens (St-Arnaud and Vujanovic 2007). *Glomus intraradices* shows beneficial effects on the development of bacterial fauna and saprotrophic fungal biomass (Albertsen et al. 2006).

10.3.2.2 *Azospirillum* Inoculants

Agricultural benefits of *Azospirillum* are well known (Okon and Labandera-Gonzalez 1994). *Azospirillum* inoculation highly influences the root exudation and development; the utilization of these phyto-stimulatory plant growth promoters can also affect the microbial fauna present in rhizospheric zone (Dobbelaere et al. 2001). In some studies, *Azospirillum brasilense* sp 245 was found to be useful in plant growth, as it helps in generation of auxins, gibberellins, and cytokinins (Steenhoudt and Vanderleyden 2000). Naiman's study suggested that when *Azospirillum* and *Pseudomonas* are co-inoculated on wheat fields, they displayed different effects on the bacterial communities flourishing on rhizospheric zone of the wheat. This inoculation altered the carbon source usage of soil microbial communities (Naiman et al. 2009). Carbon source utilization is directly related to the total microbial population capable to utilize every carbon source, and their growth reflects the functional capabilities of the microbial community. The two *A. brasilense* strains (42M and 40M) isolated from roots of maize when inoculated altered the physiological profiles of the microbial flora and fauna linked to rice (De Salamone et al. 2010).

10.3.2.3 Rhizobia Inoculants

As per several reports, rhizobia have enhanced effect on crop yield and plant development. They help in nitrogen fixation and uptake of nutrients like iron and phosphorus; stimulate plant hormones; promote the growth of favorable bacteria and fungi; and check fungal and bacterial diseases, insects, and pests. The entire rhizospheric biodiversity can be seen in the form of different functional groups which is mostly influenced by the alterations in the residual nitrogen rather than the effects of inoculation (Antoun and Prévost 2005). Further, the exact mechanisms which play key role in these changes are still not clearly known and need to be explored (Saharan and Nehra 2011).

10.3.2.4 Biocontrol Agents

Majority of rhizobacterial products have been employed as biological control for plant disease prevention instead of effecting plant nutrition uptake or dealing with abiotic stress factors (Berg 2009). Variety of microorganisms like *Bacillus subtilis*

(Dawar et al. 2010), *Trichoderma harzianum* (Mohiddin et al. 2010), and *Pseudomonas fluorescens* (Peighami-Ashnaei et al. 2009) have antagonistic effect against the diseases caused by *Sclerotium* species, *Pythium* species, *Rhizoctonia* species, and *Fusarium* species, which leads to high yield or plant growth promotion. *P. fluorescens* (Pal et al. 2000), *Pochonia chlamydosporia* (Kerry 2000), and *B. subtilis* (Khan et al. 2001) when employed are found to be effective against the diseases triggered by nematodes. Some *Pseudomonas* species are antagonist against the activity of tomato plant pathogen *Ralstonia solanacearum* (Kozdroj et al. 2004). Biocontrol agents like *Corynrbacterium glutamicumin* (Vahjen et al. 1995), *P. fluorescens* (Natsch et al. 1998), and *Streptomyces melanosporofaciens* (Prevost et al. 2006) when applied show transient effects on soil ecosystem and fungal flora and fauna, and it designates that the efficacy of the biocontrol agent may be for limited duration.

10.3.3 Effects of Co-inoculations vs Mono-inoculations

In most of the inoculations, usually single strain is applied which has displayed inconsistent results in the fields. This issue can be solved by employing different strains or different species of valuable microorganisms in the single formulation of microbes. By applying consortium of bioinoculates, there is no need of genetic engineering (Janisiewicz 1996) as different strains involve different working mechanisms to enhance the plant development, promise the efficiency and reliability that it will have positive effects on crops (Marimuthu et al. 2002). It was reported that when PGPR or AMF were inoculated, they induced slight modification on the bacterial community structure present in wheat rhizosphere (Roesti et al. 2006). The type of PGPR consortium utilized had additional effect on the bacterial community structure as compared to the AMF. Further PGPR strains employed produce an antibiotic, i.e., 2-4-diacetylphloroglucinol, which has antifungal effect; however, it does not affect the growth of AMF, and associative or synergic outcome of PGPR and AMF co-inoculation was seen.

When *Pinus pinea* was inoculated with two different strains of *Bacillus*, i.e., *Bacillus pumilus* CECT105 and *Bacillus licheniformis* CECT5160, both of these *Bacillus* strains encourage the seedling development of *P. pinea* (Probanza et al. 2002). But this positive effect was not observed when both the *Bacillus* strains were co-inoculated, maybe as a result of competition effect (Probanza et al. 2002). Further, the combo of *A. brasilense* and *B. subtilis* did not display any synergic or associative effects on tomato plants in comparison to their single inoculations. Therefore, it may be concluded that when inoculants are employed in combination, they may not necessarily show synergic effects, instead they may display competitive effects, and as a result the growth and development could be minimum or gradually disappear. Similarly, the effects on microbial flora and fauna present in soil are also uncertain or unpredictable.

10.4 Problems, Challenges, and Approaches

The current researchers are becoming more aware and focusing their work to deal with growing problems like increasing urbanization and growing population. It is expected that by 2050, about 10 billion people would inhabit the planet. With increase in population, many issues will also arise, putting more pressure to produce food, fiber, and energy resources with simultaneous sustainable approach. The growing demands cannot be avoided; however, this will put immense risk to nonrenewable resources like fossil fuels, water, energy resources, agricultural soil, etc. Further, with more and more expanding industries, contamination is also at its highest peak (Browne et al. 2013). Emission of greenhouse gases is causing the rise in earth's temperature, disturbing the environmental stability, and giving rise to various stressful scenarios which affect both agriculture and natural systems (Duarte et al. 2006). Problems like salinity of soil, drought, nutrition deficiency, diseases, soil erosion, pests, crop destruction due to natural calamities, loss of biodiversity, deforestation, landscape fragmentation, use of chemicals, etc. are affecting humans either directly or indirectly (Vitousek et al. 1997).

In view of these issues, sustainable agricultural practices and various approaches are being implemented to meet the demands without hampering the natural ecosystems; this can be achieved only when there is balance between the three major interacting domains, i.e., environment, society, and economy. The balanced interaction cycle between these three domains can finally give the true meaning to the "sustainable development" approach (Altieri 2004). In the concept of sustainability, the vital issues are regarding depletion of nonrenewable resources, controlling pests and pathogens, suitable methods for recycling soil nutrients, dealing with abiotic stress, maintaining the vitality of soil microbes (which depends on soil microbes), etc. for the global ecosystems and human welfare (Zancarini et al. 2013; Prasad et al. 2014, 2017b). Majority of these issues can be resolved by using microbial services (Zolla et al. 2013). Microorganisms can be exploited after the identification of their beneficial functions/features in terms of both cost-effective and ecological sustainability.

10.5 Conclusions

The discussion in this chapter regarding development and uses of some novel bioformulations will definitely be useful in sustainable agroecosystem. The application of microbial consortium is an essential constituent of agroecological practice, which is a reliable technology whose time has come to sustain the soil and fulfill the requirement of food and feed. These microbes in the bioformulations have been successfully employed in several parts of the globe and with encouraging results, that with time this notion of utilizing microbial consortium as bioformulations will certainly grow. In the case of underdeveloped, developing, and developed world, where agricultural inputs are synthetic and quite expensive, the application of bioformulations conquers an insignificant but developing role in organic agriculture development. Additionally, the microbial consortium in bioformulations also acts as biocontrol and stress manager and in many phytoremediation approaches. The cost-effectiveness and easy availability of bioformulations have made it a choice of farmers and scientists, since this is also a step toward organic agriculture. According to one survey carried in the USA, it was found that both organic and conventional growers are taking interest in growing and consuming organic products, since such products are not having side effects on health as caused by chemically growing agriproducts. Rzewnicki (2000) suggested that in the coming years the bioformulations demand will have huge market potential. Globally, the sale of organic products grew by 8% in the year 2010, which is expected to increase by 27% by the year 2020 (Komorowska 2014). In relation to organic production using organic manure and bioformulations, encouraging growth has been seen and still continued in the main European markets and in the case of the USA, and the viewpoint regarding bioformulations for coming years is very positive. Interestingly, China's organic market has grown four times in the last 5 years only. Moreover, in the case of Brazil, the organic produce has shown the growth rate of 40%, which is quite amazing. Regarding Asia, the market analysts forecast that organic sales using bioformulations is expected to grow by 20% a year over the next coming 3 years. All over the globe, 37 mh of land are now farmed organically, and most of the land also utilizes the microbes in one form or another. India has to work hard to achieve the good growth of organic farming using microbial bioformulations. The agricultural universities and institutions working on bioformulations development can work on these aspects using the help of state agricultural departments.

References

Agro news (2014) Biofertilizers market–global industry analysis, size, share, growth, trends and forecast, 2013–2019. Available online http://news.agropages.com/News/NewsDetail-11612–e.htm

Albertsen A, Ravnskov S, Green H, Jensen DF, Larsen J (2006) Interactions between the external mycelium of the mycorrhizal fungus *Glomus intraradices* and other soil microorganisms as affected by organic matter. Soil Biol Biochem 38(5):1008–1014

Altieri MA (2004) Linking ecologists and traditional farmers in the search for sustainable agriculture. Front Ecol Environ 2(1):35–42

Antoun H, Prévost D (2005) Ecology of plant growth promoting rhizobacteria. In: PGPR: biocontrol and biofertilization. Springer, Dordrecht, pp 1–38

Ardakani MR, Pietsch G, Moghaddam A, Raza A, Friedel JK (2009) Response of root properties to tripartite symbiosis between lucerne (*Medicago sativa* L.), rhizobia and mycorrhiza under dry organic farming conditions. Am J Agric Biol Sci 4:266–277

Arora NK, Khare E, Maheshwari DK (2010) Plant growth promoting rhizobacteria: constrains in bioformulation, commercialization, and future strategies. In: Maheshwari DK (ed) Plant growth and health promoting bacteria microbiology. Springer, Berlin, pp 97–116

Artursson V, Finlay RD, Jansson JK (2006) Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. Environ Microbiol 8:61–70

Barea JM (1997) Mycorrhiza/bacteria interactions on plant growth promotion. In: Plant growth-promoting rhizobacteria, present status and future prospects. OECD, Paris, pp 150–158
Bashan Y, de-Bashan LE, Prabhu SR, Hernandez JP (2014) Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant Soil 378:1–33
BCC Research (2010) Biopesticides: the global market report CHM029C, Wellesley
Berg G (2009) Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture. Appl Microbiol Biotechnol 84(1):11–18
Berny P (2007) Pesticides and the intoxication of wild animals. J Vet Pharmacol Ther 30:93–100
Bhattacharjee SG, Sharma D (2012) Effect of dual inoculation of Arbuscular Mycorrhiza and *Rhizobium* on the chlorophyll, nitrogen and phosphorus contents of pigeon pea (*Cajanus cajan* L.). Adv Microbiol 2:561–564
Bonaterra A, Camps J, Montesinos E (2005) Osmotically induced trehalose and glycine betaine accumulation improves tolerance to desiccation, survival and efficacy of the postharvest biocontrol agent *Pantoea agglomerans* EPS125. FEMS Microbiol Lett 250:1–8
Brar SK, Verma M, Tyagi RD, Valéro JR (2006) Recent advances in downstream processing and formulations of *Bacillus thuringiensis* based biopesticides. Process Biochem 41(2):323–342
Bravo A, Likitvivatanavong S, Gill SS, Sobero NM (2011) *Bacillus thuringiensis*: a story of a successful bioinsecticide. Insect Biochem Mol Biol 41:423–431
Browne P, Barret M, Morrissey JP, O'Gara F (2013) Molecular based strategies to exploit the inorganic phosphate-solubilization ability of *Pseudomonas* in sustainable agriculture. Mol Microbial Ecol Rhizosphere 1:615–628
CAB International Centre (2010) The 2010 world wide biopesticides market summary. CAB International Centre, Wallingford
Cavagnaro TR, Jackson LE, Six J, Ferris H, Goyal S, Asami D, Scow KM (2006) Arbuscular mycorrhizas, microbial communities, nutrient availability, and soil aggregates in organic tomato production. Plant Soil 282(1–2):209–225
Chen YP, Rekha PD, Arun AB, Shen FT, Lal WA, Young CC (2006) Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl Soil Ecol 34:33–41
Colt JS, Cyr MJ, Zahm SH, Tobias GS, Hartge P (2007) Inferring past pesticide exposures: a matrix of individ-ual active ingredients in home and garden pesticidesused in past decades. Environ Health Perspect. 115:248–254
CPL (2006) Biopesticides 2007. CPL Business Consultants, Wallingford
Dawar S, Wahab S, Tariq M, Zaki MJ (2010) Application of *Bacillus* species in the control of root rot diseases of crop plants. Arch Phytopathol Plant Protect 43(4):412–418
De Salamone IE, Di Salvo LP, Ortega JS, Sorte PM, Urquiaga S, Teixeira KR (2010) Field response of rice paddy crop to *Azospirillum* inoculation: physiology of rhizosphere bacterial communities and the genetic diversity of endophytic bacteria in different parts of the plants. Plant Soil 336(1–2):351–362
Dobbelaere S, Croonenborghs A, Thys A, Ptacek D, Vanderleyden J, Dutto P, Labandera-Gonzalez C, Caballero-Mellado J, Aguirre JF, Kapulnik Y, Brener S (2001) Responses of agronomically important crops to inoculation with *Azospirillum*. Funct Plant Biol 28(9):871–879
Dorigo U, Lefranc M, Leboulanger C, Montuelle B, Humbert JF (2009) Spatial heterogeneity of periphytic microbial communities in a small pesticide–polluted river. FEMS Microbiol Ecol 67:491–501
Duarte CM, Alonso S, Benito G, Dachs J, Montes C, Pardo Buendía M, Ríos AF, Simó R, Valladares F (2006) Global change. Impact of human activity on the Earth system. CSIC Superior Council of Scientific Investigations, Madrid
Fenske RA, Day EW Jr (2005) Assessment of exposure for pesticide handlers in agricultural, residential and institutional environments. In: Franklin CA, Worgan JP (eds) Occupational and residential exposure assessment for pesticides. Wiley, Chichester, pp 13–43

Gao X, Lu X, Wu M, Zhang H, Pan R, Tian J, Li S, Liao H (2012) Co-inoculation with rhizobia and AMF inhibited soybean red crown rot: from field study to plant defense-related gene expression analysis. PLoS One 7(3):e33977. https://doi.org/10.1371/journal.pone.0033977

Gelernter WD (2007) Microbial control in Asia: a bellwether for the future? J Invertebr Pathol 95:161–167

Global Industry Analysts (2015) Global biopesticides market to reach US$2.8 billion by 2015, according to a new report by global industry analysts, Inc. Available online http://prweb.com/printer/8041130.htm

Grand View Research (2015) Biofertilizers market analysis by product (nitrogen fixing, phosphate solubilizing), by application (seed treatment, soil treatment) and segment forecasts to 2022. Available online. http://www.grandviewresearch.com/industry–analysis/biofertilizers–industry

Harwood RWJ, Lee MSK, Lisansky SG, Quinlan R (2007) Current worldwide markets for biopesticides and success factors for the business. In: Proceedings of the XVIth international plant protection congress/BCPC international congress. Crop Science and Technology, Glasgow, pp 598–599

Industrial Equipment News (2011) Biopesticides market to reach $1 billion in 2010. Available online http://www.ien.com/article/biopesticides–market–to/8648

Janisiewicz W (1996) Ecological diversity, niche overlap, and coexistence of antagonists used in developing mixtures for biocontrol of postharvest diseases of apples. Phytopathology 86:473–479

Jia Y, Gray VM, Straker CJ (2004) The influence of Rhizobium and arbuscular mycorrhizal fungi on nitrogen and phosphorus accumulation by *Vicia faba*. Ann Bot 94:251–258

John RP, Tyagi RD, Brar SK, Surampalli RY, Prévost D (2011) Bio-encapsulation of microbial cells for targeted agricultural delivery. Crit Rev Biotechnol 31(3):211–226

Johnsen K, Jacobsen CS, Torsvik V (2001) Pesticide effects on bacterial diversity in agricultural soils: a review. Biol Fertil Soils 33:443–453

Kadouri D, Jurkevitch E, Okon Y, Castro-Sowinski S (2005) Ecological and agricultural significance of bacterial polyhydroxyalkanoates. Crit Rev Microbiol 31:55–67

Kerry BR (2000) Rhizosphere interactions and the exploitation of microbial agents for the biological control of plant-parasitic nematodes. Annu Rev Phytopathol 38(1):423–441

Kesavachandran C, Pathak MK, Fareed M, Bihari V, Mathur N, Srivastava AK (2009) Health risks of employees working in pesticide retail shops: an exploratory study. Indian J Occup Environ Med 13:121–126

Khan MR, Khan N, Khan SM (2001) Evaluation of agricultural materials as substrate for mass culture of fungal biocontrol agents of fusarial wilt and root-knot nematode diseases. Ann Appl Biol (TAC-21 Suppl) 22:50–51

Komorowska M (2014) Innovative bioformulations for seed treatment. Preliminary assessment of functional properties in the initial plant growth phase. Przemysl chemiczny. 93:959–963

Kozdroj J, Trevors JT, Van Elsas JD (2004) Influence of introduced potential biocontrol agents on maize seedling growth and bacterial community structure in the rhizosphere. Soil Biol Biochem 36(11):1775–1784

Leggett M, Leland J, Kellar K, Epp B (2011) Formulation of microbial biocontrol agents–an industrial perspective. Can J Plant Pathol 33:101–107

Liang LZ, Zhao X, Yi XY, Chen ZC, Dong XY, Chen RF, Shen RF (2013) Excessive application of nitrogen and phosphorus fertilizers induces soil acidification and phosphorus enrichment during vegetable production in Yangtze River Delta, China. Soil Use Manag 29:161–168

Linderman RG (1988) Mycorrhizal interactions with the rhizosphere microflora: the mycorrhizosphere effect. Phytopathology 78(3):366–371

Mahajan A, Gupta RD (2009) Bio-fertilizers: their kinds and requirement in India. In: Mahajan A, Gupta RD (eds) Integrated nutrient management (INM) in a sustainable rice-wheat cropping system. Springer, Dordrecht, pp 75–100

Maiyappan S, Amalraj ELD, Santhosh A, Peter AJ (2010) Isolation, evaluation and formulation of selected microbial consortia for sustainable agriculture. J Biofertil Biopestic 2:109–121

Mandal A, Patra AK, Singh D, Swarup A, Masto RE (2007) Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresour Technol 98:3585–3592

Marimuthu S, Subbian P, Ramamoorthy V, Samiyappan R (2002) Synergistic effect of combined application of *Azospirillum* and *Pseudomonas fluorescens* with inorganic fertilizers on root rot incidence and yield of cotton. J Plant Dis Protec 109(6):569–577

Marrone PG (2007) Barriers to adoption of biological control agents and biological pesticides. CAB Rev: Perspect Agri Vet Sci Nutr Natur Resour, CAB International, Wallingford, pp 2–51

Mendes R, Kruijt M, de Bruijn I, Dekkers E, van der Voort M, Schneider JH, Piceno YM, DeSantis TZ, Andersen GL, Bakker PA, Raaijmakers JM (2011) Deciphering the rhizosphere microbiome for disease-suppressive bacteria. Science 332(6033):1097–1100

Messele B, Pant LM (2012) Effects of inoculation of *Sinorhizobium ciceri* and phosphate solubilizing bacteria on nodulation, yield and nitrogen and phosphorus uptake of chickpea (*Cicer arietinum* L.) in Shoa Robit Area. J Biofertil Biopestic 3:1000129

Micro Market Monitor (2015) North America biofertilizer market by application (cereals & grains, fruits & vegetables, pulses & oilseeds), by type (nitrogen fixing biofertilizers, phosphate solubilizing biofertilizers, potash mobilizing biofertilizers), by source, by geography –analysis and forecast to 2019. Available online http://www.micromarketmonitor.com/market/north–america–bio–fertilizer–5250154124.html

Mitchell CC, Westerman RL, Brown JR, Peck TR (1991) Overview of long-term agronomic research. Agron J 83:24–25

Mohiddin FA, Khan MR, Khan SM, Bhat BH (2010) Why *Trichoderma* is considered super hero (super fungus) against the evil parasites? Plant Pathol J 9(3):92–102

Morel MA, Castro-Sowinski S (2013) The complex signaling network in microbe-plant interaction. In: Arora NK (ed) Plant microbe symbiosis: fundamentals and advances. Springer, New Delhi, pp 134–149

Morel MA, Braña V, Castro-Sowinski S (2012) Legume crops, importance and use of bacterial inoculation to increase the production. In: Goyal A (ed) Crop plant. InTech, Rijeka, pp 217–240

Morel MA, Cagide C, Minteguiaga MA, Dardanelli MS, Castro-Sowinski S (2015) The pattern of secreted molecules during the co-inoculation of alfalfa plants with *Sinorhizobium meliloti* and *Delftia* sp. strain JD2: an interaction that improves plant yield. Mol Plant-Microbe Interact 28:134–142

Moses M, Johnson ES, Anger WK, Burse VW, Horstman SW, Jackson RJ (1993) Environmental equity and pesticide exposure. Toxicol Health 9:913–959

Naderifar M, Daneshian J (2012) Effect of different nitrogen and biofertilizers effect on growth and yield of *Brassica napus* L. Int J Agric Crop Sci 4:478–482

Naiman AD, Latrónico A, de Salamone IE (2009) Inoculation of wheat with *Azospirillum brasilense* and *Pseudomonas fluorescens*: impact on the production and culturable rhizosphere microflora. Eur J Soil Biol 45(1):44–51

Nakhro N, Dkhar MS (2010) Impact of organic and inorganic fertilizers on microbial populations and biomass carbon in paddy field. Soil J Agron 9:102–110

Natsch A, Keel C, Hebecker N, Laasik E, Défago G (1998) Impact of *Pseudomonas fluorescens* strain CHA0 and a derivative with improved biocontrol activity on the culturable resident bacterial community on cucumber roots. FEMS Microbiol Ecol 27(4):365–380

Okon Y, Labandera-Gonzalez CA (1994) Agronomic applications of *Azospirillum*: an evaluation of 20 years worldwide field inoculation. Soil Biol Biochem 12:1591–1601

Olsson PA, Bååth E, Jakobsen I, Söderström B (1996) Soil bacteria respond to presence of roots but not to mycelium of arbuscular mycorrhizal fungi. Soil Biol Biochem 28(4–5):463–470

Paikray S, Malik V (2010) Microbial formulation for widespread used in agricultural practices: google patents

Pal KK, Tilak KV, Saxena AK, Dey R, Singh CS (2000) Antifungal characteristics of a fluorescent *Pseudomonas* strain involved in the biological control of *Rhizoctonia solani*. Microbiol Res 155(3):233–242

Pandey P, Maheshwari DK (2007) Bioformulation of *Burkholderia* sp. MSSP with a multispecies consortium for growth promotion of *Cajanus cajan*. Can J Microbiol 53:213–222

Peighami-Ashnaei S, Sharifi-Tehrani A, Ahmadzadeh M, Behboudi K (2009) Interaction of different media on production and biocontrol efficacy of *Pseudomonas fluorescens* P-35 and *Bacillus subtilis* B-3 against grey mould of apple. J Plant Pathol 1:65–70

Pimentel D, Acquay H, Biltonen M, Rice P, Silva M, Nelson J (1992) Environmental and economic costs of pesticide use. Bioscience 42:750–760

Prevost K, Couture G, Shipley B, Brzezinski R, Beaulieu C (2006) Effect of chitosan and a biocontrol Streptomycete on field and potato tuber bacterial communities. BioControl 51(4):533–546

Probanza A, Garcıa JL, Palomino MR, Ramos B, Mañero FG (2002) *Pinus pinea* L. seedling growth and bacterial rhizosphere structure after inoculation with PGPR *Bacillus* (*B. licheniformis* CECT 5106 and *B. pumilus* CECT 5105). Appl Soil Ecol 20(2):75–84

Prasad R, Kumar V, Prasad KS (2014) Nanotechnology in sustainable agriculture: present concerns and future aspects. Afr J Biotechnol 13(6):705–713

Prasad R, Bhola D, Akdi K, Cruz C, Sairam KVSS, Tuteja N and Varma A (2017a) Introduction to mycorrhiza: Historical development. In: Mycorrhiza (eds. Varma A, Prasad R and Tuteja N) Springer International Publishing AG 1–7

Prasad R, Bhattacharyya A, Nguyen QD (2017b) Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Front Microbiol 8:1014. doi: 10.3389/fmicb.2017.01014

Prasad R, Gill SS, Tuteja N (2018) Crop Improvement Through Microbial Biotechnology. Elsevier (ISBN: 9780444639882)

PRWEB (2014) Europe bio fertilizer market is expected to reach $4,582.2 million in 2017 new report by MicroMarket Monitor. Available online http://www.micromarketmonitor.com/market/europe–bio–fertilizer–4637178345.html

Roesti D, Gaur R, Johri BN, Imfeld G, Sharma S, Kawaljeet K, Aragno M (2006) Plant growth stage, fertiliser management and bio-inoculation of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria affect the rhizobacterial community structure in rain-fed wheat fields. Soil Biol Biochem 38(5):1111–1120

Rzewnicki P (2000) Ohio organic producers: final survey results. Online. Ohio State University Extension, College of Food Agricultural and Environmental Sciences. Bulletin, Special Circular 174

Saharan BS, Nehra V (2011) Plant growth promoting rhizobacteria: a critical review. Life Sci Med Res 21(1):30–39

Sanborn M, Kerr KJ, Sanin LH, Cole DC, Bassil KL, Vakil C (2007) Non cancer health effects of pesticides: systematic review and implications for family doctors. Can Fam Physician 53:1712–1720

Schisler DA, Slininger PJ, Behle RW, Jackson MA (2004) Formulation of *Bacillus* spp. for biological control of plant diseases. Phytopathology 94:1267–1271

Schubler A, Schwarzott D, Walker C (2001) A new fungal phylum, the Glomeromycota: phylogeny and evolution. Mycol Res 105(12):1413–1421

Seneviratne G, Zavahir JS, Bandara WM, Weerasekara ML (2008) Fungal-bacterial biofilms: their development for novel biotechnological applications. World J Microbiol Biotechnol 24(6):739

Smith RS (1992) Legume inoculant formulation and application. Can J Microbiol 38(6):485–492

Spyrou IM, Karpouzas DG, Menkissoglu-Spiroudi U (2009) Do botanical pesticides alter the structure of the soil microbial community. Microb Ecol 58:715–727

St-Arnaud M, Vujanovic V (2007) Effect of the arbuscular mycorrhizal symbiosis on plant diseases and pests. In: Mycorrhizae in crop production. Haworth, New York, pp 67–122

Steenhoudt O, Vanderleyden J (2000) *Azospirillum*, a free-living nitrogen-fixing bacterium closely associated with grasses: genetic, biochemical and ecological aspects. FEMS Microbiol Rev 24(4):487–506

Stenersen J (2004) Chemical pesticides: mode of action and toxicology. CRC Press, Boca Raton

Tajini F, Trabelsi M, Drevon JJ (2012) Combined inoculation with *Glomus intraradices* and *Rhizobium tropici* CIAT899 increases phosphorus use efficiency for symbiotic nitrogen fixation in common bean (*Phaseolus vulgaris* L.). Saudi J Biol Sci 19:157–163

Tavasolee AN, Aliasgharzad G, Salehijouzani MM, Asgharzadeh A (2011) Interactive effects of arbuscular mycorrhizal fungi and rhizobial strains on Chickpea growth and nutrient content in plant. Afr J Microbiol 10:7585–7591

Thakore Y (2006) The biopesticide market for global agricultural use. Ind Biotechnol 2:194–208

Trivedi P, Pandey A, Palni LM (2005) Carrier-based preparations of plant growth-promoting bacterial inoculants suitable for use in cooler regions. World J Microbiol Biotechnol 21:941–945

Vahjen W, Munch JC, Tebbe CC (1995) Carbon source utilization of soil extracted microorganisms as a tool to detect the effects of soil supplemented with genetically engineered and non-engineered *Corynebacterium glutamicum* and a recombinant peptide at the community level. FEMS Microbiol Ecol 18(4):317–328

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277(5325):494–499

Zancarini A, Lépinay C, Burstin J, Duc G, Lemanceau P, Moreau D, Munier-Jolain N, Pivato B, Rigaud T, Salon C, Mougel C (2013) Combining molecular microbial ecology with ecophysiology and plant genetics for a better understanding of plant–microbial communities' interactions in the rhizosphere. Mol Microbial Ecol Rhizosphere 1:69–86

Zayadan BK, Matorin DN, Baimakhanova GB, Bolathan K, Oraz GD, Sadanov AK (2014) Promising microbial consortia for producing biofertilizers for rice fields. Microbiology 83:391–397

Zolla G, Bakker MG, Badri DV, Chaparro JM, Sheflin AM, Manter DK, Vivanco J (2013) Understanding root-microbiome interactions. Mol Microbial Ecol Rhizosphere 1:743–754