BIOFERTILIZERS APPLICATION FOR SUSTAINABLE ECONOMIC DEVELOPMENT: ADVANTAGES AND CONSTRAINTS

Contents

ADVANTAGES OF USING BIOFERTILIZERS IN AGRICULTURE

Biofertilizers are defined as formulations containing either living or latent cells of efficient strains of microorganisms that facilitate the uptake of nutrients form crop plants. They execute this pivotal role through interactions in the plant rhizosphere when applied through seed or soil.

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Biofertilizers accelerate certain microbial processes in the soil which supplement nutrients in a form easily assimilated by plants. Biofertilizers supply nutrients through the natural processes of nitrogen fixation, solubilizing phosphorus and stimulating plant growth through the synthesis of growth-promoting substances. Currently, biofertilizers are an important component of the integrated nutrient supply system.

Biofertilizers like *Rhizobium*, *Azotobacter*, *Azospirillum* and blue-green algae (BGA) are in use for decades. However, these microorganisms are very often not as efficient in natural surroundings as desired; thus, application of massively multiplied cultures of selected efficient microorganisms is needed to accelerate the microbial processes in soil. Therefore, the use of biofertilizers is strongly recommended by the competent professionals to guarantee good plant growth and higher production yields.

Biological fertilization (or biofertilization) as a process of application of natural inputs including fertilizers offers significant advantages in the efforts of contemporary agriculture to reduce the use of chemical fertilizers and pesticides. The most important advantages can be summarized as follows:

Low cost and easy application techniques

Biofertilizers are cost effective relative to chemical fertilizers. They differ from chemical and organic fertilizers because they do not directly supply any nutrients to crops and constitute cultures of special bacteria and fungi with relatively low installation cost. The use of biofertilizers can improve the productivity per unit area in a relatively short time. They have lower manufacturing costs and reduced use costs, especially regarding nitrogen and phosphorus use. Their easy way of application consumes smaller amounts of energy. This means lower costs associated with the process of fertilization that can be directly translated into profitable benefits for farmers. In this sense, application of biological fertilizers can bring benefits from an economic point of view, since biofertilizers are a cost effective and renewable source of plant nutrients to substitute the chemical fertilizers for sustainable agriculture.

Most commonly biofertilizers are in powder, carrier-based form. The carrier usually is lignite. The lignite has high organic matter content and holds more than 200% water. This high water content enhances the growth of the microorganisms. The application method for this type of biofertilizers is preparation of slurry, which is applied to the seeds. This method was considered universal until recently.

At present, however, another method, dry complex fertilizer for direct soil application, has been developed. It consists of granules (1–2 mm) made from tank bed clay (TBC) and baked at 200 °C in a muffle furnace, which helps to sterilize the material and gives porosity to the granules. The baked granules are soaked in a suspension of desired bacteria grown in a suitable medium overnight. The clay granules are air-dried at room temperature under aseptic conditions. They contain about 10^9 bacteria per gram of granules. These granules are suitable for field application along with seeds. However, the quantity of biofertilizer to be applied is slightly higher than that in seed application.

Increase of the yield with additional 15-35% in most vegetable crops

Biofertilizer is a technological innovation that has the potential to increase crop yield, reduce production cost and improve soil condition.

Biofertilizers can be considered as supplementary to chemical fertilizers. When they are applied as seed or soil inoculants, they multiply and participate in the nutrient cycling, thus benefiting the crop productivity. Biofertilizers have great potential to improve crop yields through environmentally better nutrient supplies. They provide reserve plant nutrients. It is reported that biofertilizers increase crop yields by 20–30% and stimulate plant growth. The efficiency of biofertilizer use is the key characteristic that ultimately contributes to the increase of the crop yield.

There are numerous examples that biofertilizers positively affect the crop yield. For instance, Vital N®, an organic biofertilizer registered with the Philippine FPA, is a powder formulation that induces extensive growth in roots of crops like corn, rice, banana, garlic, orchids and onion. It contains *Azospirillium*, a beneficial bacterium that produces the plant-growth-stimulating substance indole-3-acetic acid (IAA), resulting in higher growth yield.

There are reports that the overall performance of potato crops is positively influenced by application of green manures (cowpea and *Crotolaria* sp.): 30% yield improvements. The increased productivity values verify the efficiency of biofertilizers in agricultural production. On the other hand, some physicochemical properties of the soil are improved and environmental impacts due to the prolonged use of chemical fertilizers are gradually mitigated.

Furthermore, 10% increases in the yield per hectare have been observed for crops treated with arbuscular mycorrhizal (AM) fungi, combined with increased resistance of the plants to the action of pathogenic microorganisms. Additionally, when AM is combined with nitrogen-fixing bacteria or compost extracts, this combined use of biofertilizer on crops provides better yield performance, higher by a factor of two, and better physical characteristics of individual plants.

A trial investigating the feasibility of biofertilizers prototypes based on native bacteria from rice crops reported 10% increases in yield production by using the mixtures, from 7,625 kg/ha to 8,500 kg/ha. The main outcomes deal with the importance of biofertilizers to get higher revenues and increase productivity, in order to achieve, progressively, sustainable agricultural development.

The application of the aquatic fern–cyanobacteria symbiotic association *Azolla–Anabaena* as a biofertilizer in rice paddies of northern Italy allowed obtaining yields close to 40 kg nitrogen/ha during a 3-month period and verifying increases in the growth rate of rice. Furthermore, higher resistance of some of the rice species to the presence of herbicide Propanil was evidenced.

Provision of nitrogen and several growth hormones

Biofertilizers contribute to the maintenance of stable nitrogen (N) concentrations in the soil. They replace chemical nitrogen by 25%. Thus, nitrogen-fixing microorganisms play an important role in nitrogen supply by converting atmospheric nitrogen into organic forms usable by plants. Use of biological N_2-fixation technology can contribute to a decrease in the N fertilizer application and to the reduction of environmental risks. *Azotobacter* (free-living N_2-fixer) plays an important role in the nitrogen cycle in nature due to its diverse metabolic potential. In addition to N_2 fixation, this microorganism has the ability to synthesize and secrete considerable amounts of biologically active substances, among which the vitamins thiamine and riboflavin, nicotinic acid, pantothenic acid, biotin; the plant-growth hormones heteroxins, gibberellins. These biologically active substances help in modification of the nutrient uptake by the plants. Another free-living N_2-fixer, *Azospirillum*, is reported to produce plant-growth-promoting substances indole acetic acid (IAA) and indole butyric acid (IBA) and increase the rate of mineral uptake by plant roots, resulting in the enhancement of plant yield.

It is well known that most plants form symbiotic associations with the arbuscular mycorrhizal fungi (AMF) acting as bio-ameliorators. They have the potential to considerably enhance the rhizospheric soil characteristics. This, in turn, leads to improved soil structure and promotes plant growth under normal as well as stressed conditions. The results revealed that the AMF-induced enhancement in nutrient uptake promotes various biologically important metabolites. Among them of special importance are the plant hormones, including GA and auxin, which play a unique role in plant growth regulation under both normal and stress conditions. The activity of phytohormones like cytokinin and IAA is also significantly higher in plants inoculated with AMF. Higher hormone production results in better growth and development of the plant.

Do not cause atmospheric pollution but increase soil fertility

The use of biofertilizers is not only cost effective; it also augments the problem of environmental pollution. They are environmentally friendly because their use not only prevents damaging the natural resources but also helps to some extent to free the plants of precipitated chemical fertilizers. Biofertilizers promote the reduction of environmental impacts associated with the excessive use of chemical fertilization. Thus, their use in organic farming, sustainable agriculture, green farming and non-pollution farming contribute to implementation of healthy environment policies at national, regional and global level.

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All types of crops grown in different agro-ecologies can benefit from the use of biofertilizers. Continuous use of biofertilizers enables the microbial population to remain and build up in the soil and helps in maintaining soil fertility contributing to sustainable agriculture.

Biofertilizers keep the soil environment rich in all kinds of micro- and macro-nutrients via nitrogen fixation, phosphate and potassium solubilization or mineralization, release of plant-growth-regulating substances, production of antibiotics and biodegradation of organic matter in the soil. Growing crops using biofertilizers is advantageous in protecting the soil from degradation. Biofertilizers can mobilize nutrients that favour the development of biological activities in soils. In this way, they prevent micro-nutrient deficiencies in plants and guarantee better nutrient uptake and increased tolerance to drought and moisture stress, all factors that strongly contribute to soil fertility.

Excretion of antibiotics and acting as pesticides

The use of biofertilizers can promote antagonism and biological control of phytopathogenic organisms. Thus, positive effect on soil microbiology is exerted: suppression or control through competition of pathogenic populations of microorganisms present on the soil.

Strategies for biological control of fungal species in crops include application of biofertilizers obtained from biological digestion to control target pests and pathogens. Through the siderophores and antibiotics produced by them, biofertilizers are antagonistic to foliar or rhizosphere pathogenic bacteria, fungi and insects.

Arbuscular mycorrhizal fungi (AMF) have the potential to reduce damage caused by soil-borne pathogenic fungi, nematodes and bacteria. Meta-analysis has shown that AMF generally decrease the effects of fungal pathogens. A variety of mechanisms have been proposed to explain the protective role of mycorrhizal fungi. The major mechanism is nutritional, because plants with a good phosphorus status are less sensitive to pathogen damage. Non-nutritional mechanisms are also important, because mycorrhizal and non-mycorrhizal plants with the same internal phosphorus concentration may still be differentially affected by pathogens. Such non-nutritional mechanisms include activation of plant defense systems, changes in exudation patterns and concomitant changes in mycorrhizosphere populations, increased lignification of cell walls and competition for space for colonization and infection sites.

Recently, several fungal endophytes, like *Trichoderma* spp. (Ascomycota) and Sebacinales (Basidiomycota, with *Piriformospora indica* as a model organism), which are distinct from the mycorrhizal species, have attracted scientific attention. These fungi are able to live at least part of their life cycle away from the plant, to colonize its roots and to transfer nutrients to their hosts, using mechanisms that are not clear yet. They are receiving increasing attention, both as plant inoculants easier to multiply *in vitro* and as model organisms for revealing the mechanisms of nutrient transfer between fungal endosymbionts and their hosts.

Trichoderma spp. have been extensively studied and used for their biopesticidal (mycoparasitic) and biocontrol (inducer of disease resistance) potential, and have been exploited as sources of enzymes by biotechnological industries. Now it is speculated (on the basis of convincing evidence) that *Trichoderma* spp. also induce many plant responses. Among the most important of them are the increased tolerance to abiotic stress, nutrient use efficiency and organ growth and morphogenesis.

On the basis of these effects, these fungal endophytes may be regarded as both biopesticides and biostimulants.

Improvement of physical and chemical properties of soil

Biofertilizers contribute to better physical conditions in the soil through improvement of structure and aggregation of soil particles, reducing compaction and increasing the pore spaces and water infiltration. They improve soil structure and allow better tilth; ensure better soil aeration and water percolation, reducing soil erosion. Biofertilizers serve as major food source for microbial populations thus keeping the soil alive. They also contribute to soil chemical conditions through improvement of nutrients availability in the soil, leaving free elements to facilitate their absorption by the root system; improved capacity of nutrients' exchange in the soil resulting in favourable effects on the physico-chemical stability of soils. As a result of the good structure and improved stability provided to the soil, root growth is promoted.

The maintenance of good soil structure in all ecosystems is largely dependent on mycorrhizal fungi. Formation and maintenance of soil structure is influenced by soil properties, root architecture and management practices. The use of machines and fertilizers are considered to be responsible for soil degradation, which is a key component of soil structure. Mycorrhizal fungi contribute to maintain good soil structure through the following processes:

- growth of external hyphae into the soil creates a skeletal structure that holds soil particles together;
- external hyphae create conditions that are conducive to the formation of micro-aggregates;
- enlargement of micro-aggregates by external hyphae and roots to form macro-aggregates;
- directly tapping carbon resources of the plant to the soils. This process influences the formation of soil aggregates, because soil carbon is crucial to form organic materials necessary to cement soil particles. The hyphae of AM fungi are more important in this

process than the hyphae of saprotrophic fungi due to their longer residence time in soil. In addition, AM fungi produce glomalin (12–45 mg/cm^3), a specific soil protein with still unknown biochemical nature. Glomalin has a longer residence time in soil than hyphae, allowing for a long persistent contribution to soil aggregate stabilization. The residence time for hyphae is considered to vary from days to months and for glomalin from 6 to 42 years. Glomalin is considered to stably glue hyphae to soil. The mechanism is the formation of a 'sticky' string-bag of hyphae which leads to the stability of aggregates.

Enhance crop yield even under ill irrigated conditions

Biofertilizers increase the water and nutrient holding capacity of the soil and also increase the drainage and absorption of moisture in soils, especially in those with structural deficiencies or lack of nutrients. They increase the tolerance towards drought and moisture stress. In this way, they increase the crop yield even in plantations that lack sufficient natural water supply or irrigation. For instance, AM association improves the hydraulic conductivity of roots at lower soil water potentials and this improvement is one of the factors contributing towards better uptake of water by plants. Moreover, leaf wilting after soil drying does not occur in mycorrhizal plants until the soil water potential is considerably lowered (approx. 1.0 MPa). Mycorrhiza-induced drought tolerance can be related to factors associated with AM colonization such as improved leaf water and turgor potentials and maintenance of stomatal functioning and transpiration, greater hydraulic conductivities and increased root length and development.

Eco-friendly and pose no danger to the environment

The most important and contributing function of biofertilizers is considerable reduction in environmental pollution and improvement of agro-ecological soundness. Biofertilizers are eco-friendly organic agro-input compared to chemical fertilizers. They cause no harm to ecosystems and are valuable to the environment as they enable reduced use of chemical fertilizers in the production of crops worldwide. Namely due to their eco-friendly characteristics, the demand for biofertilizers is on the increase during the last decade. Their activities influence the soil ecosystem and produce supplementary substances for the plants. Providing continuous supply of balanced micronutrients to the plants and eliminating plantar diseases, biofertilizers enhance the maintenance of plant health and contribute to soil ecology. The provided food supply and impelled growth of beneficial microorganisms contribute to sustain the ecological balance. In the long run, biofertilizers are planned to complement and, where appropriate, replace conventional chemical fertilizers, resulting in economic and environmental benefits.

LIMITATIONS

The term 'biofertilizer' itself means 'live fertilizer'. The quality of biofertilizers demands not only profound study of the microbial characteristics, but also elucidation of the precautions and limitations of their use at laboratory, at production as well as at field level.

Biofertilizers offer a wide range of opportunities for the development of better agro-practices due to the advantages and benefits provided for the soil, crops and farmers. However, there are limitations of these practices that are clearly recognized. These limitations demand feasibility studies to be carried out to find better solutions for each particular case in agricultural activities.

Some of the major limitations are shown below.

Lack of regulatory acts and facilities for testing the samples

Future research on biofertilization should be focused on identifying the options available to tackle the issues and offer valid frameworks for development of environmentally friendly practices around the world that allows improvements on the efficiency and consequent supply of product for the industry in the global economies. What is more, technical tests must be carried out to verify their safety at global scale. Current research of the use of biofertilizers in different regions of the world is necessary to obtain a framework that facilitates the development of future investigations in the agricultural sector and, consequently, promote the reduction of environmental impacts associated with the continuous use of chemical fertilization.

Insufficient popularization of biofertilizers and low level of farmer acceptance

Biofertilizers are a technological innovation that has the potential to increase crop yield, reduce production cost and improve soil conditions. Biofertilization comprises an innovative approach to sustainable agriculture involving scientists, technology developers, policymakers, entrepreneurs and farmers.

Despite having various potential activities, biofertilizers have not yet gained popularity among farmers for adequate acceptance. There are a variety of factors affecting the acceptance of biofertilizers by farmers. By knowing the different constraints or problems faced by farmers in the use of biofertilizers, the extent of acceptance of biofertilizers can be increased by tackling these issues and problems.

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Biofertilizers are inexpensive to farmers because of low costs and their ability to help improve soil structure, texture and water-holding capacity in agriculture. However, farmers are not aware of biofertilizers' usefulness in increasing crop yields sustainably. Their lack of awareness about the concentration, time and method of biofertilizer application; about the efficacy of biofertilizers compared to their familiarity with the use of conventional and tested inorganic fertilizers is a serious limitation of their wide-scale application. In addition to these main problems, there are also financial (lack of timely availability of financing and/or lack of subsidies), technical (lack of guidance from expert personnel, non-availability of biofertilizers and inadequate water facilities) and other constraints (lack of interest or confidence in different biofertilizer practices).

Furthermore, entrepreneurs lack knowledge and skills for correct application of biofertilizers and have limited capacity to support considerable marketing strategies about this. The policymakers need to strengthen their efforts in popularization of the adoption and diffusion of biofertilizers, and encouragement of their competition with the well-established inorganic fertilizer industry. The concept behind the government technology promotion policy is to inform the farmers about the broad range of alternative technologies available and proved efficient. Promotion of active farmer participation in adaptive research to enhance product understanding and at the same time to create demand is envisaged.

In order to promote sustainable agriculture, both central and local government authorities have to support extensive application of biofertilizers. In this context, emphasis in attaining higher yield and better quality crops is being given in several directions: the production of inoculants; extension programmes for the farmers to know how to apply inoculants; and demonstration and awareness programmes to show farmers the benefits of inoculated crops.

Possible risks for the safety of consumers and the physicochemical and biological stability of soils

High contents of ammonia can burn the foliage and roots of plants; the presence of manure could increase the amount of weed flora. The presence of heavy metals (e.g. mercury, chromium and lead) pose a threat due to their carcinogenic potential and their capability of bio-accumulation and bio-magnification in the food chain. For this reason, the use of manure to fertilize soils should be well assessed.

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Decline in the population of bacteria under certain climate conditions and influence of surrounding microflora and fauna

Biofertilizers, on application to seeds, roots or soil, mobilize the availability of nutrients by their biological activity in particular, and help build up the microflora and in turn the soil health in general. However, their bio-efficacy is dependent on many biotic and abiotic factors. Unfavourable climate conditions (changes in temperature and humidity) can cause a decline in the bacterial populations. Similar negative effects on bacterial quantity can be imposed by the surrounding microflora and fauna, which compete with the introduced beneficial microorganisms for nutrients and other vital factors in the micro-ecological niches. Antagonistic microorganisms already present in the soil compete with microbial inoculants and often do not allow their effective establishment by outcompeting the inoculated population.

Another contributing factor are the non-specific host–inoculant relationships, different physical and chemical edaphic conditions, poor competitive ability against native strains and deficiency of adequate formulations. For instance, the efficiency of plant-associated nitrogen fixation by diazotrophic bacteria may be hampered by a limited supply of energy and substrates.

Requirements for application

Extensive and long-term application may result in accumulation of salts, nutrients and heavy metals that could cause adverse effects on plant growth, development of soil organisms, water quality and human health. Excessive application can generate extreme levels of nitrogen, ammonia and salts that could lead to significant reduction of plant growth and problems for farmers and the soil. Large volumes are required for land application due to low contents of nutrients, in comparison with chemical fertilizers, because main macronutrients may not be available in sufficient quantities for growth and development of plants. Also, there could be some nutritional deficiencies caused by the low transfer of micro- and macro-nutrients.

Thus, the implementation of biofertilization techniques requires monitoring of environmental variables involved in metabolic processes, acquisition of biological inputs, capital investment, time and trained personnel. In order to achieve sustainable agriculture, it is necessary to implement plans, programmes, projects and initiatives directed towards the minimization of environmental impacts and consequent benefits for farmers and producers.

CONSTRAINTS IN BIOFERTILIZER PRODUCTION TECHNOLOGY

An important characteristic common to most biofertilizers is the unpredictability of their performance. It is of vital importance for the consistency of biofertilizers performance to be improved. And the performance is dependent on the biofertilizer production technology.

Although the biofertilizer technology is a low-cost and ecofriendly technology, several constraints limit its application or implementation. These constraints are technological, infrastructural, financial, environmental, human resources unawareness and quality. The different constraints affect the production technology, the marketing and use of biofertilizers.

Technological constraints

Despite significant improvement of biofertilizer technology over the years, the progress in the field of biofertilizer production technology is not satisfactory. Technological constraints faced by both organic and conventional farmers in adoption of organic farming practices are focused on the following aspects:

Strains for production

The use of inappropriate, less efficient strains for production of biofertilizers may lead to insufficient population of microorganisms and is a significant constraint. Lack of region-specific strains is one of the major constraints, as biofertilizers are not only crop specific, but soil specific, too. Additionally, the selected strains should have competitive ability over other strains in a range of environmental conditions, and ability to survive both in broth and in inoculant carriers. Another problem may be the high level of contaminants. Therefore, the good biofertilizer product must contain a good effective strain in an appropriate population and should be free from contaminating microorganisms. Furthermore, in case of problematic soil (acidic, saline and alkaline), biofertilizers cannot be used due to decrease in their efficiency; when the temperature is high, biofertilizer application is also not successful. Poor application of biofertilizers can be expected in case of unfavourable phosphorus in the soil. And finally, biofertilizers tend to mutate during fermentation, thereby raising the production and quality control cost. Extensive research work on this aspect is urgently needed to eliminate such undesirable changes.

Technical personnel

Inadequate and inexperienced staff and not technically qualified one can contribute to technical problems with biofertilizer technology.

Lack of technical information and skills about the biofertilizers application is a big constraint with high intensity, because farmers are not given proper instructions about the application aspects. Poor organization of the application process and lack of spare time for applying biofertilizers at sowing time; lack of knowledge about inoculation technology by the extension personnel and the farmers is another important problem.

The majority of the marketing sales personnel do not know proper inoculation techniques. Biofertilizers, being living organisms, require proper handling, transport and storage facilities.

Quality of production units

Lack of qualified technical personnel in production units may lead to inappropriate manipulations and handling during production.

Quality of carrier material

Unavailability of good quality carrier material or use of different carrier materials by different producers without knowing the quality of the materials can impose serious problems in biofertilizers application efficiency.

Unavailability of a suitable carrier, in which bacteria are allowed to multiply, is a major reason for shortening the shelf-life of biofertilizers. According to the availability and cost at the production site, a choice of carrier material must be made. The good quality carrier must have good moisture-holding capacity, be free from toxic substances, serializable and readily adjustable to pH 6.5–7.0. Under climate conditions where extremes of soil and weather conditions prevail, there is yet no suitable carrier material identified capable of supporting the growth of biofertilizers. Better growth of bacteria is obtained in sterile carrier and the best method of sterilization is gamma irradiation.

In the carrier-based biofertilizers, the microorganisms have a shelf-life of only six months. They are not tolerant to UV rays and temperatures higher than 30 °C. The population density of these microbes is only 10^8 cfu/ml at the time of production. This count decreases day by day. That is why the carrier-based biofertilizers are not very effective and popular among the farmers.

Possible measures to mitigate these disadvantages include use of sterile carriers and installing centralized unit of sterilizing facilities; identification of common carrier materials in different countries based on availability and recommendation to the producers.

The alternative is the so-called liquid biofertilizers. Liquid biofertilizers are special liquid formulations containing not only the desired microorganisms and their nutrients, but also special cell protectants or chemicals that promote formation of resting spores or cysts for longer shelf-life and tolerance to adverse conditions. The shelf-life of the microbes in the liquid biofertilizers is two years with a count as high as 10^9 cfu/ml, which is maintained constant. They are tolerant to high temperatures (55 °C) and UV radiation. Since these are liquid formulations, the application in the field is also very simple and easy. They are applied using hand sprayers, power sprayers, fertigation tanks, etc. Developing suitable alternate formulations, i.e. liquid inoculants/granular formulations for all bioinoculants requires standardizing the media, the method of inoculation etc., for the new formulations.

Quality of inoculants

Production of inoculants without understanding the basic microbiological techniques threatens the inoculants quality, and consequently, their efficiency. Possible removal of the seed coat from the seed due to rubbing the seed with the biofertilizers solution, may result in poor germination. Inadequate formulation of the products can be a serious barrier to the commercialization of biofertilizers. However, the demand for high-quality inputs triggers innovation improvement.

To formulate inoculants of high quality, the following considerations have to be taken in mind: identification/selection of efficient location/crop/soil-specific strains for N-fixing, P, Zn-solubilizing and absorbing (mycorrhizal) to suit different agro-climatic conditions; applying biotechnological methods for strain improvement; exchanging cultures between countries of similar climatic conditions and evaluating their performance for better strains for a particular crop; checking the activity of cultures during storage to avoid natural mutants.

Shelf-life of inoculants

The short shelf-life (usually 6 months) requires efficient storage. This discourages entrepreneurs from producing more than what they could immediately sell as well farmers from buying more than what they immediately need because they could not store the product for a long time. In countries where most biofertilizers in the marketplace are imported, generally they are not tailored to the local conditions in terms of shelf-life and storage environments. For instance, the biofertilizers that require storage in a cool place for an extended shelf-life are not suitable for countries where temperatures are usually quite high. Thus, it is not surprising that such products will not meet the quality standards, probably as a result of loss of viability in the inappropriate storage conditions. That is why product formulation, taking into consideration product shelf-life under variable storage and handling conditions is critical.

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The problems in the development of the biofertilizer sector usually are associated with low demand due to lack of awareness and understanding of biofertilizers. In many cases production remains a challenge, not only because of its cost, but also because of the restricted demand and the poor delivery mechanisms that could be associated with the particular requirements for handling and storage conditions. The product shelf life, the quality of carrier materials, the storage conditions (e.g. temperature), handling (e.g. transportation), as well as the presence of contaminants affect the field performance and, consequently, the adoption rate. It is thus important to improve the shelf-life of locally formulated biofertilizers in various storage conditions to ensure product viability over a significant time period.

Infrastructural constraints

Facilities for production

Non-availability of suitable facilities for production is a major infrastructural constraint. In addition, inadequate availability of inputs and unavailability of inputs at appropriate time impose another problem. Employing microbiologists in production units to monitor the production and developing cold storage facilities in production centers is a good approach do improve production infrastructure.

The biofertilization suffers from inadequate marketing facilities and unavailability of regular information regarding the use of biofertilizers, which imposes uncertainty and risk among farmers.

Equipment

This shortage of essential equipment, power supply, etc. leads to increase in labour, since the production process in this case is slow and time consuming.

Laboratory, production, storage space

Space availability for laboratory, production, storage, etc. is very important. To expand biofertilizer production, extra land is needed for growing, for example, green manure crops. The lack of provision of subsidy and trading of biofertilizers at reasonable price are other important issues. However, the increasing demand for biofertilizers and the awareness among farmers in the use of biofertilizers have facilitated the biofertilizer manufacture and encouraged the entrepreneurs to get into biofertilizer production.

Storage of inoculant packets

Lack of facility for cold storage of inoculant packets is a problem that threatens the quality of biofertilizers, since they have to be stored in a cold place, away from direct sun or hot wind. The inadequate storage facilities may expose biofertilizers to high temperatures, which are unfriendly conditions.

Financial constraints

Funding

Non-availability of sufficient funds and problems in getting bank loans. The total use and price of inorganic fertilizers are continuously increasing. Meanwhile, their use efficiency is still low, and pressure on their application is coming from regulation/environmental concerns. Alternatively, biofertilizers (which are renewable) offer high use efficiency, relatively low price and minimal environmental impact. Currently, their financing is getting better.

Sale returns

The biofertilizer industry is vulnerable to less returns by sale of products in smaller production units. This is a major problem to face, since organization and operation of large production facilities is multifaceted due to scientific, economic, social and environmental problems that have to be handled.

Physical and environmental constraints

Seasonal demand for biofertilizers

Biofertilizers demands are of seasonal character, and so are the requirements for biofertilizers supply, and consequently, the biofertilizer production and distribution are done only in a few months a year. The biofertilizer producers face a challenge to design improved formulations tailored to local conditions and to supply them in a mode that satisfies the spatial and temporal variability of crop responses. Thus, extensive research on the technology to develop formulations that could satisfy these requirements is necessary. Without such research, the producers will not be able to benefit from the full potential of biofertilizers.

Cropping operations

Biofertilizers application is generally dependent on the other cropping operations demanding simultaneous activities. The short span of sowing/planting in a particular locality must be considered as well. Thus, biofertilizers must be applied in appropriate doses following a recommended method. Any use of adhesives of poor quality and with strong doses of plant protection chemicals will diminish the biofertilizer application efficacy.

Soil characteristics

Soil characteristics like salinity, acidity, drought, water logging, etc. are of vital importance. High soil temperature or low soil moisture, extreme acidity or alkalinity in soil, poor availability of phosphorus and molybdenum and presence of high native population or presence of bacteriophages, should all be considered, since they affect the microbial growth and crop response. For instance, the field performance of biofertilizers, e.g. *Rhizobium* inoculants, is affected not only by the characteristics of the plant (crop genotype) and the inoculant (the microbial strain), but also by the environmental conditions (i.e. soil and weather), as well as the agronomic management.

The soil pH affects the microbial population, i.e. the survival of the strain, and the nutrient availability. This effect and the relationships to the availability and survival of beneficial microorganisms in the biofertilizers applied to soil can be summarized in the following way:

Indicator	pH decrease	pH increase
Population of beneficial microorganisms (*Rhizobia*)	Low	High
Strain survival	Low	Low at pH > 8.5

A healthy population of microorganisms beneficial to plant growth is difficulty to support at low pH. Legume response to inoculation in soils with high acidity is week. Limited availability of nutrients such as P and Mo negatively affects nodulation and reduces the *rhizobia* population, thus having a negative effect on BNF. In mineral soils, the pH range of maximal P availability is quite small (pH 6.5–7.0). For Mo the situation is relatively acceptable for 5.5 < pH < 7.5, where the availability of Mo increases with pH, particularly at pH levels > 7 and drastically decreases at pH < 5.5. High reactivity of phosphate with aluminum, iron and calcium, and the subsequent precipitation makes it unavailable to plants. In field conditions with acidic pH and low phosphorus, the nodulation process is adversely affected. In such situations, lime could be used to improve the pH.

The effect of soil pH, however, depends on the type of biofertilizers. Several field experiments using cyanobacteria on different types of soils found that urea N inputs could be reduced by 25–35% with application of this biofertilizer in the cultivation of rice in acidic and saline soils. However, the product was less effective in calcareous and neutral soils. Hence, the efficacy of a biofertilizer depends on whether the microbial strain can survive in field conditions. Consequently, there is a need to understand the optimum pH for each type of biofertilizer in the various agro-ecological conditions.

The availability of nutrients is another important soil characteristic that has to be considered. This is particularly true for phosphorus (P). It has been shown that application of inorganic P fertilizers in combination with biofertilizers increased soybean yields by ≈ 47% over the negative control in soils with low P content. Furthermore, *rhizobial* activity and BNF is enhanced by increased availability of P. Hence, P is among the limiting nutrients for legume BNF in most plants and selected biofertilizers have shown the ability to improve the plant P uptake. This means that a reasonable approach to improve BNF efficiency through improved P availability and uptake is to perform co-inoculation of effective *rhizobia* inoculants and biofertilizers. Thus, in arid saline soils where the availability of P and K (potassium) is limited, use of phosphate-solubilizing bacteria (PSB) showed improved availability of the nutrients. Following the improvement of the performance of chemical P fertilizers by PSB, some companies have promoted increased sales of chemical fertilizers alongside biofertilizers. Combination of biofertilizers and low-cost fertilizer materials such as rock phosphate may represent an important market opportunity.

Soil drought represents a stressful environment for plants to survive. Biofertilizers application can prove to be of benefit in drought-prone areas, since it enables the crops to survive through improved water-use efficiency. This potential of biofertilizers is a promising tool to augment seasonal drought episodes that significantly contribute to yield gaps. For instance, field trials in Africa have shown that *rhizobia* inoculation improves the yield of alfalfa, fenugreek, cluster bean, field pea and common bean grown in drought conditions.

The putative mechanisms of action of selected biofertilizers to improve crop resistance to drought are as follows:

Biofertilizer	Mechanism of action	Benefits
Mycorrhiza (AMF)	Enhance the host capability for osmotic adjustment.	• Continued water uptake even in dry soils (and soils becoming dryer) contributing to plant survival in drought conditions; • Increased photosynthesis and better osmotic adjustment under drought stress.
***Rhizobium* (BNF)**	Production of phytohormones	• Changes in root morphology and physiology resulting in increased water and nutrient uptake; • Enhanced nodulation, increased dry weight of nodules, better nitrogen fixation and crop yield.

Human resources and quality constraints

Staff competence

Inadequate human, financial and material resources can compromise the production and application of biofertilizers. Lack of technically qualified staff in the production units is a serious problem. This constraint is in direct connection with the lack of proper training and adoption of technical qualifications for production of biofertilizers. Improving the technical and human capacity for quality control of biofertilizers has also been identified as critical for adequate biofertilizer market realization. Supportive government policies therefore appear important to ensure that only high-quality biofertilizers are legally sold.

Educational and training in biofertilizers

In general, the main problem is lack of proper training in organic farming and inadequate knowledge of field functionaries about organic farming. Additionally, lack of suitable training in the production techniques and skills about improved methods of biofertilizers making; lack of awareness about the concentration, time and method of biofertilizer application; lack of knowledge about different pesticides are other important issues that have to be considered in the view point of human resources and quality constraints.

Technical training on the production and quality control to the producers; rendering technical advice and projects to manufacturers; organizational training to the extension workers and farmers to popularize the technology; to arrange better and wider dissemination of information are measures that should be considered.

Production techniques

The most important difficulties arise due to ignorance on the quality of the product by the manufacturer due to lack of quality specifications and requirements by both the production management and consumers.

The governmental support for the production and use of biofertilizers may lead to promising results. Thus, various Asian countries have achieved increased use of biofertilizers through support of the government. For example, in Thailand, the production and use of biofertilizers drastically increased as a result of the support of the Ministry of Agriculture to the sector. A similar government initiative was reported in India.

Many countries have mandated the national biotechnology institutions to address the biosafety issues to ensure that products are safe to plants, animals, humans and the environment, while creating an enabling environment for innovation. The trends in investment in biofertilizer production are indicating positive results. However, given the risk imposed by the short shelf-life and the lack of guarantee of offtake of biofertilizers, the production resource generation is very limited.

Quality specifications and quick quality control methods

Quality control and regulation of biofertilizers is important to ensure conformity to prescribed standards, product safety and efficacy. The sale of poor quality biofertilizers through corrupt marketing practices results in loss of faith among farmers. Poor quality biofertilizers can be expected in the market when the quality control framework is not well-defined, resulting in poor field performance. Adherence to specified quality standards by manufacturers is important to ensure only adequate quality products are allowed at the market. Recurrent monitoring of products in the market is important to ensure product quality in the full commercialization chain.

An assessment on biofertilizer products revealed that a great number of the product formulations did not match the product labels due to the absence of the active ingredients or the presence of contaminants. Enforcement of quality standards could significantly contribute to mitigate this constraint. Well-defined requirements for quality would also facilitate the approval process of biofertilizers.

The non-availability of quality provisions and quick quality control methods is the reason why biofertilizer production and specifications are vulnerable to compromising. For instance, in

South Africa, the first commercially manufactured inoculant was produced in 1952. However, due to poor quality products on the market, in the 1970s an independent quality control system was introduced to ensure that the products could match the best quality inoculants produced in other countries.

Quality standards at par among different countries could facilitate the regional trade. One approach is to align the standards with those in countries with significant history of biofertilizers use, such as India, South Africa, New Zealand, France, Australia and Canada among others. In that way, the consumer protection will be improved, while facilitating trans-boundary trade. For instance, in these countries, *rhizobium*-based inoculants should contain at least 5×10^7–10^9 colony forming units (CFU) of the active ingredients (i.e. microorganism strains) per gram of the biofertilizer product. Meanwhile, no contaminants should be detected at 10^5 dilutions. In Australia, Canada, China, New Zealand, Thailand, the USA, as well as most of the countries in the EU, self-regulation of the biofertilizer industry has been established. Here, the industry pays for the quality control. In countries like Canada, France and Uruguay, the government plays a role in the quality control of biofertilizers. For instance, in France, despite the long history of biofertilizer use in agricultural production, manufacturers are still required to generate sufficient data to support the quality, efficacy and safety of novel products.

Regulation

Lack of effective regulation on biofertilizers is among the greatest contributors to low availability and adoption of the products. Research to improve the agricultural application of biofertilizers is often disrupted through lack of awareness, infrastructure and human resources, as well as the absence of a supportive regulatory and policy framework. The potential benefits of biofertilizers can remain largely unexploited due to inadequate policy and regulatory framework. Low demand for biofertilizers can be possibly a result of bad regulatory environment.

Effective regulatory environments can significantly reveal the potential of biofertilizers use. To ensure that proven technologies do not compete with poor-quality biofertilizers in the marketplace, effective regulations for improved quality control are required to promote fair trade and market growth for biofertilizers. Lack of appropriate regulatory framework about the quality of the products leads to poor facilitation of production, distribution and use of biofertilizers.

Another obstacle in the use of biofertilizers is the difficult procedures in registering new products. Poor management of fertilizers and supplements (e.g. biofertilizers) registration can rise obstructions to innovation and limit the accessibility to novel products that otherwise would improve farmers' competitiveness. Most EU, North American and some Asian countries have established appropriate regulations in order to control such difficulties and create a favourable business environment for biofertilizers.

For example, the Canadian Food Inspection Agency (CFIA) has well-structured and precisely defined procedures accepted by the industry for the registration of biofertilizers. This is a good practice in clear administrative processes that allow biofertilizer businesses to operate in a secure environment and to attract new investors in the biofertilizer industry.

However, in many countries, no such administrative guidelines have been made available through regulations, resulting in difficulties in the introduction of new biofertilizer products on the market. There is a need for a common framework covering policies, laws, regulations, standards and institutional arrangements to guarantee the prospect of the biofertilizers industry. The key constraints that such a framework will combat include:

- Inadequate or incomplete policies and guidelines for regulation of biofertilizers and biopesticides;
- Multiple and often overlapping regulatory mandates by responsible authorities;
- Limited capacity, including staff, skills and laboratory for product monitoring;
- Inadequate enforcement of quality control for biofertilizers and biopesticides;
- Lack of biofertilizer- and biopesticide-specific regulations, standards and guidelines;
- Weak institutional arrangements with limited collaboration between relevant authorities.

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