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The Role and Future Potential of Bio-Fertilizers in Indian Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Only imports and subsidies have been able to guarantee the availability and affordability of chemical fertilisers made from fossil fuels at the farm level in India. Because of their non-toxicity, affordability, ease of use, and environmental friendliness, biofertilizers are currently a very effective substitute for chemical fertilisers. By making naturally available nutrients in the soil or environment advantageous to plants, they also serve as an adjunct to agrochemicals. If farmers and producers have the proper kind of access to information gleaned through experience and communication, this commodity could eventually show promise economically. The Indian government has been attempting to blend more advanced agrochemicals with biofertilizers. This study focuses on the success and failure issues in the Indian context to increase the potential for sustainable agriculture growth. Additionally, it emphasises the necessity of high levels of innovation, active involvement in scientific research and development, public awareness campaigns, and enticing business organisations and policy leaders to show interest in this area.

Keywords: Rhizobium; biofertilizers; nitrogen; bacteria; phosphorous.

1. INTRODUCTION

In the cultivation of crops, fertilisers are crucial. Traditionally, it is thought to be essential for preserving soil fertility and increasing agricultural output. Because chemical fertilisers are so expensive, not all farmers can afford them. They can choose to use bio-fertilizers to get around this. Chemical fertilisers oppose the Earth's biological cycle, whereas biofertilizers support it. They facilitate the slow release of nutrients to plants and the breakdown of organic materials (Carter, 1967). It is well recognised that biofertilizers have a limited impact on plant nutrition enhancement. In addition to fixing atmospheric nitrogen in the soil, biological fertilisers promote beneficial bacteria that aid in crop production (Saikia & Jain, 2007). Organic soil fertility management is guided by the philosophy of “feed the soil to feed the plant (Devi et al., 2023a). Over-reliance on synthetic fertilisers in agricultural production has negative long-term impacts on plant nutrition and soil health. Because plants need too many hazardous nutrients, chemical fertilisers with high nutrient concentrations can be extremely harmful to plant roots and can inhibit root growth. Bio-fertilizers' low nutrient content allows plant roots to obtain more nutrients without endangering the plants. Crops grown in most soils in India suffer from-deficiencies of one or more micronutrients, even though the soils often contain apparently adequate total amounts of the respective elements (Karandashov & Bucher, 2005, (Rao, 1982). The kinds and severity of deficiencies vary depending on the agro-ecological conditions, crop genotype, soil type and management (Devi et al., 2023b).

While "fertiliser" refers to natural nutrients, "bio" refers to living things such as bacteria, fungi, and cyanobacteria. In the framework of sustainable agriculture, biofertilizer is regarded as highly significant and has enormous potential for Indian farms and society at large. This kind of fertiliser adapts to sociological, environmental, and socioeconomic shifts. There are several kinds of biofertilizers that are big enough and have diverse ways of working. All biological fertilisers play a part in speeding up biological nitrogen metabolism; some can dissolve phosphate, while others promote hormone synthesis. Instead of relying on the known creatures found in bio-fertilizers, a bio-fertilizer can contain a single bacterial system, primarily earthworms, or a combination of these living organisms (Kennedy et al., 2004). These are all related in a positive way. The present practical nitrogen need is lowered by 20–40% with biofertilizer. To improve anti-crop phosphorus fixation, it aids in the incorporation of nutrient fertilisers. It contributes to biochemical nutrient availability and increases soil fertility. By striving to enhance the plants' general growth, the bacteria promote the plants' development (Philippot & Germon, 2005).

The easiest approach to describe biofertilizers is as biologically active products or microbial inoculants, which are formulations that include one or more beneficial bacterial or fungal strains in reasonably priced and easily digestible carrier materials (Rahman et al., 2009). Their objective is to add, preserve, and mobilise agricultural nutrients in the soil. When applied to soil, plant surfaces, or seeds, biofertilizer—as defined by Mazid et al. (2011a)—contains living microorganisms that colonise the plant's interior or rhizosphere and promote development by increasing the amount of primary nutrients accessible to the host plant. The organic components in organic fertilisers have the potential to either directly or indirectly increase soil fertility through breakdown. Likewise, it is improper to use the terms "biofertilizers," "green manure," "manure intercrop," and "organic supplemented chemical fertiliser" interchangeably. The substantial long-term environmental advantages of biofertilizers exceed the drawbacks of chemicals. Because technology at the farm level pollutes water less than chemical fertilisers and even produces some organic manures, its advantages can be transferred to other farms and enterprises (Mahdi et al., 2010). The advantages of the novel technique for halting soil degradation were not immediately apparent, in contrast to artificial fertilisers, which provide results quickly. These unique liquid formulations, called liquid bio-fertilizers, include the targeted microorganisms and their nutrients together with extra chemicals or cell protectants that promote the establishment of dormant spores or cysts for a longer shelf life and resilience to hostile environments. It is also necessary for the farmer to take a big initial risk and learn by doing. In addition, the farmer has to pay for skill development, trial and error, and a substantial upfront risk (Gandhi & Saravanakumar, 2009). The producer firms' high levels of uncertainty about the product's demand or viability for sale deter investment, particularly if it is irreversible (Ghosh, 2004). The triumphs or failures of early entrants who take the initiative or those who conduct study for a better product might share important knowledge with others and eventually with society. Additionally, soil fertility and crop yield can be raised by purposefully reproducing cultures of specific soil organisms, also referred to as biofertilizers or microbial inoculants. The majority of focus and effort is focused on the commercial exploitation of these biological processes, despite the fact that legumes have long been known to increase soil fertility and their role in biological N-fixation, which was discovered more than a century ago. Latent cells of these microorganisms are applied to seed, soil, or composting areas to boost the number of effective strains of nitrogen fixing, phosphate solubilizing, or cellulolytic microorganisms and accelerate the microbial processes that increase the availability of nutrients that plants can readily absorb (Mazid et al., 2011b). The usage of PGR as a biofertilizer is not universal. In addition to biofertilizers, certain bacteria also serve as bio-pesticides, preventing unwanted microbes from growing and promoting plant growth. Similarly, because they may stimulate plant growth by producing phytohormones, bacteria are regarded as bio enhancers rather than biofertilizers (Mazid et al., 2011c). Biofertilizers fix atmospheric nitrogen, solubilize insoluble soil phosphates, and produce plant development compounds in the soil, both on their own and in combination with plant roots. This greatly increases the fertility of the soil. Biofertilizers are microorganisms with cells, such as organic material decomposers, P solubilizers, S oxidizers, and N fixers. These compounds, referred to as bio inoculants, boost the growth and yield of plants when they are given them (Khan et al., 2011a). We currently require organic fertilisers, such biofertilizers, to reduce our reliance on fertiliser N. Research on biofertilizers was conducted. According to studies on biofertilizers conducted both inside and outside of India, legumes including beans, soybeans, chickpeas, and pigeon peas may fix 50–500 kg of atmospheric nitrogen per hectare under the correct environmental circumstances. Therefore, by combining biological wastes with beneficial bacteria that supply organic nutrients to agricultural products, biofertilizers offer a safe method of using renewable resources to improve soil fertility. As an environmentally friendly supplement to fertilisers for strong plant growth, biofertilizers are gaining popularity. They could preserve the supply of nutrients required by plants while significantly reducing the demand for synthetic fertilisers. Through biological stress, these bio-inputs—also known as bio-inoculants—are substances that include live cells of different microorganisms and have the ability to mobilise nutritionally significant components from non-usable states. They enhance plant output and growth when treated (Khan and Naeem, 2011; Mazid et al., 2012a). The extensive use of hazardous pesticides and synthetic fertilisers on crops has made modern agriculture increasingly unsustainable. This has led to significant problems with food safety and security, stagnating farmer income, and rising crop expenses. Soil health has significantly declined due to the negligent and inconsistent use of chemical pesticides, fertilisers, particularly urea, and a lack of organic manures.Bio-fertilizers are renewable, environmentally benign, and proven natural fertilisers made from living things. In other words, these are extremely efficient providers of agricultural nutrients and are the living crops of microorganisms. Because biofertilizers are non-toxic and do not serve as immediate symptom relief, their effects on plant growth and productivity are extensive, long-lasting, and permanent. They remain effective even after millions of years of exploitation. The yield of crops and soil is greatly influenced by biofertilizers. Using inexpensive, environmentally acceptable bio-fertilizers can help Indian crops meet between 40 and 50 percent of their total nutritional needs. Nitrogen-fixing biofertilizers, phosphate-solubilizing biofertilizers, zinc-solubilizing biofertilizers, mycorrhizal fungi, and plant growth-promoting rhizobacteria are among the various types of biofertilizers that are categorised based on their properties, modes of action, sources, and forms.

2. PRODUCTION AND DEMAND

In India, interest in the usage of bio-fertilizers is rising as the country continues to look for sustainable and ecologically safe agricultural nutrition sources. As additional sources become available in the market, a growing number of individual farmers and entire village communities are using bio-fertilizers. Bio-fertilizers are becoming more widely accepted as more schools and institutions include them in their agricultural education curricula. A number of other factors, including the farmer's age, education, social involvement, decision-making skills, access to credit, and information sources, all influence the adoption of such agro-based modern technologies.

Due to the usage of chemical fertilisers, the total hectares under biofertilizers changed quickly, reaching a maximum of over 10 million hectares, but are now steadily dropping. This is based on the finding that, although many farmers have access to biofertilizers, chemical fertilisers have become more widely available over time, whilst biofertilizers are still more scarce and difficult for the majority of farmers to obtain. The market for biofertilizers has been expanding. The Green Revolution's interventions in the 1970s and early 1980s focused on the extensive use of chemical pesticides, fertilisers, and modern machinery, which upset the balance between agriculture and the natural world. Continuous cropping and frequent soil cultivation contribute to the breakdown of soil aggregates and the removal of organic matter, which reduces soil fertility and production (Devi et al., 2023c). Reopening the heritage and implementing modern practices and technology in ways that are sensitive to and integrate with the local environment would be part of the third agricultural revolution and return to green, as many Indian industries and the government have realised over time that significant progress cannot be imagined by ignoring the environment to address modern agricultural needs.

The production of biofertilizers is always driven by demand, and one of the most crucial parts of promoting biofertilizers is creating demand among farmers. The nation presently generates more biofertilizers than it needs due to the great programmes in biofertilizer production and widespread use by the government and research institutes (Parr et al., 1994). For instance, plant responses to Azotobacter inoculation in irrigated wheat varied from 34 to 247 kg/ha in a sample of 411 field tests conducted across districts; in 342 of these cases, the results were deemed significant.

However, improper and careless chemical fertiliser applications have a negative impact on the environment, the microbial ecology, and the natural equilibrium of soil agricultural ecosystems, which leads to a general decrease in crop productivity. If biofertilizers produce certain long-term and societal benefits that private individuals would not be willing to pay for, at least not until the benefits are "visible," then there is a case to be made for spreading the cost among a larger number of receivers or the general public (Bohlool et al., 2022). Therefore, we must reduce our reliance on chemicals and seek out affordable, eco-friendly technologies. As a result, the biofertilizer business is seeing a noteworthy trend. Over the past century, several families have lived in India. Even though the Green Revolution has made India a self-sufficient food producer, there is still no room for complacency. An assessment of the present supply and demand situation, marketing strategies, networks, and government actions related to biofertilizer price in India was also given by Sharma and Upadhyay (2007).

Although the green revolution significantly increased the amount of food available, sustainability was not given enough thought. Future agricultural expansion that depends on chemical fertilisers would cause the soil to deteriorate even more, perhaps contaminate the water supply, and put an unsustainable strain on the economy. Given the current situation, the government wants to promote their usage in agriculture while also supporting private initiative and the financial sustainability of output. In India, the only ways to ensure the availability and affordability of chemical fertilisers derived from fossil fuels at the farm level are through imports and subsidies. As a superior practice, the Indian government has been promoting the use of biofertilizers alongside fertilisers. These inputs have a number of beneficial benefits on the soil and can be more convenient and reasonably priced. Low demand from farmers, who are the product's end users, can be caused by a market's incapacity to produce the need for government intervention when the expected social benefits of a relatively new product outweigh the costs while the private benefits do not, as well as by the product's performance uncertainty and protracted learning curve. They are effective and affordable inputs that don't harm the environment as much as chemicals, according to field study. Biofertilizers can also be used as an eco-friendly substitute for organic manures and chemical fertilisers. Plants can naturally develop resistance to pests and soil-borne diseases because of the creation of antibodies and the involvement of beneficial microorganisms in the soil to improve fertility (Board, 2004). During soil treatment, 500–800g of biofertilizers are evenly mixed with 10-15 kg of FYM and applied to the soil at planting time since they require organic manures to grow, develop, and remain active in the soil. However, the All India Coordinated Pulse Improvement Project Transportation trials once again fall short of yielding consistent advantages due to the fact that distribution is a major problem in rural areas (Khan and Mazid, 2011).

Because production quality is not adequately supervised, biofertilizers are promoted. Regionally specialised strains still need to be created, and there are currently very few biofertilizers with ISI standards in place. There are few facilities and rules pertaining to biofertilizer testing, and there is a lack of long-lasting carrier material. Dry land agriculture is characterised by low yield, erratic weather patterns, and low chemical fertiliser dosages. The microorganisms utilised as biofertilizers are divided into three groups: bacteria, BGA, and fungi. Rhizobia and other biofertilizer carriers that are kept for an extended length of time are sterilised using ionising radiation (Tittabutr, 2012).

2.1 N-fixing Biofertilizers (NBF)

Nitrogen Fixing Bio-fertilizers: Nitrogen is a necessary ingredient for all metabolic processes and is required for the production of proteins and nucleic acids. The soil receives nitrogen from a variety of nitrogen-fixing organisms, including azotobacter, azospirillum, and rhizobium. Leguminous plant root nodules contain the symbiotic nitrogen-fixing bacteria Rhizobium. Some non-legumes have their roots infected by Azospirillum. As free-living diazotrophic bacteria that use different host plants for photosynthesis, Azotobacter thrives in soil. By using them, you can maximise nutrient utilisation and soil health, minimise the need of artificial fertilisers, and lessen pollution in the environment. Nonetheless, it is widely known that biofertilizers are used more widely in agriculture and that choosing the right strain of biofertilizer based on crop and soil conditions is important. Crop rotation, integrated nutrient management systems, and other cropping patterns are all compatible with bio-fertilizers, which can be used on any type of crop in any type of habitat. Despite their intrinsic qualities, biofertilizers have various drawbacks and restrictions on the circumstances in which they can be effective.

Due of insufficient oversight of manufacturing quality, Rhizobium (Family: Rhizobiaceae) biofertilizers are being promoted. Regionally specific strains still need to be created, and there are currently very few biofertilizers with ISI criteria in place. There is a shortage of durable carrier material, and there are few facilities and laws governing biofertilizer testing. Dry land agriculture is characterised by low chemical fertiliser dosages, low production, and erratic weather patterns. Fungi, bacteria, and BGA are the three types of microorganisms that are utilised as biofertilizers. Rhizobia and other biofertilizer carriers that are kept for an extended length of time are sterilised using ionising radiation (Tittabutr, 2012).

2.2 Azotobacter (Anzotobacteriaceae family)

In addition to remaining on the root surface, a sizable portion of the Azotobacter that colonises the roots also penetrates the root tissues and lives in harmony with the plants. It belongs to the Azotobacteriaceae family and is heterotrophic, aerobic, and free-living. Both neutral and alkaline soils contain azotobacters, with A being the most common species in arable soils. Chrococcum.

A is one of the several species that have been documented. Vinelandii, A. A. Beijerinckii. insignis, together with A. macrocytogenes. This bacteria has been discovered to be present in the rhizospheres of a wide variety of crop plants, such as rice (*Oryza sativa L.*), maize (*Zea mays* L.), sugarcane (*Saccharum officinarum* L.), bajra

(Pennisetum glaucum L.), vegetables, and plantation crops (Mazid et al., 2011e). They don't, however, result in any growth or visible nodules on the root tissue. These aerobic, free-living, non-symbiotic bacteria can fix up to 25 kg of nitrogen per hectare and increase yield by up to 50% in the right conditions. The peach roots with the highest levels of alkaline phosphatase activity were those treated with Azotobacter chroococcum + P fertiliser. This has been shown to help a variety of crops, such as cotton, sugarcane, vegetables, grains, and millets. The effects of Azotobacter chroococcum on vegetative growth and maize yields, as well as the consequences of inoculating wheat with this bacterium, have been studied by numerous authors.

2.3 Acetobacter

It can tolerate high quantities of sucrose and grows endophytically in sugarcane environments. Because plants release growth-promoting hormones called IAA, which promote germination and root development and ultimately aid in nutrient absorption, this bacterium can fix up to 15 kg of nitrogen per acre annually. Shares by kind have also changed, with PSB showing by far the strongest results and Azotobacters performing moderately. The quantity of units deflates the units' yearly capacity, and the reduction in rhizobium suggests that groundnut and pulse production fell short of expectations. The link between capacity and actual distribution (as opposed to production) yields a measure of capacity. The relationship between actual distribution (as opposed to production) and capacity yields a measure of capacity utilised. The greatest improvement in straw and grain production was observed in wheat plants treated with rock phosphate as a P fertiliser after being inoculated with Azotobacter + Rhizobium + VAM.

2.4 Family Azolla: Azollaceae

Azolla can be grown as a dual crop or as green manure. Azolla is planted in a field or a separate shallow pond for green manuring. This symbiotic fern grows freely on the water's surface and is found in low-lying fields and bodies of water. Before the paddy is shifted, the water in the field is drained and azolla is mixed into the soil. Additionally, Azolla's dried inoculum is pre-soaked in a 50 ppm superphosphate solution for 12 hours prior to being injected into the paddy field (Kannaiyan, 2002). It fixes 40–55 kg of N/ha, 15-20 P/ha, and 20–25 kg of K/ha, increasing the yield of flooded paddy by 10–20% in a month

2.5 Biofertilizers Required

The commercial history of biofertilizers began in 1895 when Nobbe and Hiltner introduced "Nitragin," a laboratory culture of Rhizobia. Blue green algae (BGA) and several more microbes were later found after Azotobacter. Azospirillum and Vesicular-arbuscular micorrhizae (VAM) are relatively new discoveries. N. first investigated the rhizobium symbiosis in legumes in India. V. Joshi, and commercial manufacturing started in 1956. However, a major effort to popularise and promote the input began with the Ministry of Agriculture's establishment of the National Project on Development and Use of Biofertilizers (NPDB) under the Ninth Plan. Biofertilizers are two different ways to get plant nutrients, even though they have been marketed as a supplement or complement to chemical fertilisers. It is possible to empirically verify the degree of complementarity vs substitution between the two inputs, but it is undeniable that farmers and producers are aware of the substitutability relationship and think that biofertilizers offer a number of advantages. In addition to supplying nutrients for both now and future use, certain biofertilizers also give plants growth-boosting elements, and some have been effectively stimulating composting and the efficient recycling of solid waste. By exercising control soil-borne illnesses and enhancing the health and characteristics of the soil, these organisms aid not only in reducing costs, but also efficiently using chemical fertilisers, which leads to increased yield rates (Bot and Benites (2005). In order to meet production goals, the Government. of India carried out the National Project on Development and Use of Biofertilizers (NPDB), a central sector initiative, during the Ninth Plan for the manufacturing, marketing, and distribution of biofertilizers. A Development of National Biofertilizers. With six regional centres, the centre was founded in Ghaziabad as a subordinate office of the Department of Agriculture and Cooperation. According to the coefficient of variation, the industry's variety has grown as a result of the coexistence of smaller new units with larger ones of higher vintage (Ghosh, 2004). Though there has allegedly been a minor decline in the distribution share over the last five years, this is only partially true because units with extensive distribution networks do distribute over wider territories. The MLN Farmers' Training Institute of the public sector fertiliser company IFFCO, which is based in Phulpur, Uttar Pradesh, produces various varieties of biofertilizers and distributes them in states outside of the home state.

Reiterating that new entrance has primarily been in small units, over 70% of the large units are of lengthier vintage. After March 1995, over 70% of the small units were created. Whereas all of the large units produce both types, the tiny units exhibit a tendency to specialise in either phosphate solubilizers or nitrogen fixers. Although the percentage has decreased significantly for West Bengal, whose distributions dropped to zero in 2000–02, eastern states like Bihar and Orissa are still served. North is the biggest claimant, although the distribution differs from that of chemical fertilisers they augment. Though the share in the latter scenario is even smaller, the eastern region ranks bottom in terms of both chemical and biofertilizers (Ghosh, 2004). However, if the cropped area in the areas is not included, the comparison is incomplete. When it comes to biofertilizers, the public sector's efforts, in conjunction with those of several colleges and research facilities that get state funding, must, eventually result in financial success if the technology is implemented to attract private industry since the market is open to new players.

A vast variety of agrochemicals, including various forms of organic and inorganic fertilisers, are used extensively in our contemporary agricultural practices (Brodt, 2002). Through irrigation, rainfall, drainage, etc., they were swept off from lands and into rivers, lakes, streams, and other bodies of water. When they fully embrace our natural ecology, they have a direct or indirect impact on human life, including:

1. Vegetables cultivated on soil that is rich in NO3 might cause disorders like hemoglobinemia.
1. This results in a number of illnesses, including cancer, skin discoloration, and harm to the vascular and pulmonary systems.
2. Chemical fertilisers use an imbalance in the plant body's entire mineral arrangement. For instance, too much K-treatment reduced important minerals like carotene and ascorbic acid in food.
3. decreasing soil fertility as a result of the growing discrepancy between fertiliser supply and removal.
4. Although NO3 fertilisers boost crop yield overall, protein is sacrificed in the process. Malnutrition results from consuming low-quality protein because the majority of Indians are vegetarians.
5. growing awareness of environmental risks.
6. By 2020, it is predicted that in order to reach the desired production of 321 million tonnes of food grain, 28.8 million tonnes of nutrients would be needed, but only 21.6 million tonnes will be available, resulting in a shortfall of almost 7.2 million tonnes.

Additional problems are associated with host genotype compatibility, improper handling facilities, inoculant protocols, and improper dosing. Therefore, using biofertilizers usually has no positive effects on traditional agriculture (Rivera and Fernandez, 2006). The present levels of biofertilizer production fall well short of the extremely high potential demand. Assuming that 50% of the gross cultivated area is utilised for the application of biofertilizers under different crops, the estimated amount is 348 thousand tonnes (Wiesman, 2009). The average distribution likewise declined in the first two years, suggesting that a downsizing was necessary, but it thereafter rose. Despite the generally low capacity utilisation, the downsizing might have halted the decline. The locations of biofertilizer production facilities vary depending on the source of funding. Two kinds of biofertilizer production units can be distinguished based on the source of funding:

1. Government of India (GOI)-financed units
2. Units funded by outside funding sources

With GOI assistance, 64 biofertilizer production facilities have been created thus far. Their installed production capacity exceeds 900 tonnes, and they produce more than 6000 tonnes of biofertilizers overall. In comparison to the projected demand of 235 thousand tonnes for bacterial fertilisers, the remaining 38 biofertilizer production facilities with total installed production capacity are still quite low (Choonawala, 2007).

2.6 Procedure

Biofertilizers are composed of two ingredients: microorganisms and a carrier substance. Aside from the microorganisms themselves, the carrier is the most crucial element of every composition. There are several steps in the process. Aside from outside factors, handling method errors are a major contributor to subpar performance in real-world applications. Due to their high sensitivity to temperature and other environmental conditions, these "living" inputs require close attention throughout the production, culture, distribution, and application phases. Investigating, packaging, storing, and using suitable carrier materials takes time and money. It also involves mass-multiplying a selected, capable strain of organisms in the broth media and combining high-quality, tested broth cultures of the microorganisms in the homologous carrier. Inoculants are utilised to generate as many spores as feasible. It is a good idea to promote biofertilizers as an input in addition to other fertilisers, although there is some reason to subsidise the former in order to encourage their use, considering the protection offered to chemicals (Sundar, 2002). A systematic and uniform approach to subsidy distribution must be created in order to prevent inter-unit pricing distortion and favouring some units over others. The states should be firmly guided by this standard. However, the incentives would mostly encourage farmers to test the input at fair and affordable prices, rather than directly helping particular producers. The institutes also started producing and distributing various biofertilizers, but they stopped doing so after redefining their roles to include R&D and HRD-related operations. However, a one-time grant for new units was used to promote capacity creation and production. The developmental function of a company and the strength of its sales network, which creates market and draws market feedback, were highlighted in numerous studies on technological progress as critical to its success. Larger production companies are generally expected to invest more in networks to comprehend and reach the market, but it is not unusual for companies with larger distribution networks to serve as marketing agents for smaller, underdeveloped units. In a few exceptional instances, such as NAFED, the distribution even surpasses capacity. Increased sales networking may also be advantageous for companies that now sell agricultural products (Ghosh, 2004). Given that the data does not clearly reflect the specific scope and kind of the units or possibly their parent corporations, prior experience selling biofertilizers may be interpreted as an indicative of their marketing ability (Singh, 2007). The curing time is determined by the growth rate of the microorganisms to be utilised. After curing, low-density polythene bags made of sheets 50–70 mm thick are usually used to package the biofertilizers. The product name, crop for which it is intended, manufacturing date, expiration date, nett quality intended for 0.4 hectares, storage instructions, and usage instructions for biofertilizers should all be clearly indicated on each package. Every properly tested packet need to bear the ISI-certified mark.

2.7 Limitations on the Use of Biofertilizer

1. Lack of a suitable carrier due to resource constraints
2. Market-level limitations and farmers' ignorance
3. Limited resource generation and a lack of quality assurance for the manufacture of biofertilizers
4. Seasonal and uncertain needs
5. Climate and soil conditions, as well as a lack of qualified personnel
6. Ineffective inoculation methods, the native microbial population, and fermentation-related mutation

The Indian Biofertilizer Market: Approximately 170 companies in 24 countries make biofertilizers for commercial use. In these cases, the cost, hazards, and reactions of biofertilizers would be compared to those of chemical fertilisers. NifTAL (U.S.A.) has been a significant factor in the expansion of Rhizobium inoculants. Promoting technology for environmental reasons would necessitate some degree of protection in order to reduce the price distortion between fertilisers. Australia has taken the lead in monitoring the quality of a variety of commercial goods. The Philippines established the National Azolla Programme (NAAP) in 1982 to provide farm-based technology for the application of Azolla fertiliser for rice. Currently valued at over US$30 billion, the market for agricultural products produced organically is predicted to rise at a rate of almost 8% each year. Approximately 22 million hectares of land are used for organic farming today (Sheng et al., 2009). Less than 1% of the world's conventional agricultural production and about 9% of all agricultural land are used for organic farming. This just highlights the vast potential for the development of biofertilizer. At the moment, 60 production facilities produce 10–115 tonnes per unit yearly. Several state governments also provide subsidies, sometimes up to 50% of the sales realisation, despite the fact that the techniques of subsidisation are not particularly systematic. Discrimination and subsidy manipulation are common causes of price fluctuations within an industry. Two of the most significant challenges facing producers and investors are the absence of demand and the volatile and seasonal nature of the current market. The technology is still in its early stages of development, as you may recall. The rice-dominated eastern region remains unproductive, and there has been no interest in the wheat rice that is developing in the north (Luft and Korin, 2009). Research into developing efficient, resilient, and temperature-tolerant strains is crucial for the technology's true success. The technology's potential in rice and cereals in general may receive some attention, despite the fact that its significance for crop diversification is equally worrisome (Mahmud et al., 1994). The government also has a significant role in marketing.

Three potential pathways for biofertilizers:

(a) State government through officers at the district and village levels to farmers,
(b) State Marketing Federation to farmers through cooperative organisations and
(c) Agro-industries of the State

companies to farmers via an agro-service facility. The manufacturers, however, are free to sell through their own sales network or the market. Over the course of four years, the number of units rose from 62 to 95 and then to 122 in 2002, a 53% increase. The total capacity increased by 12%, according to data on units reporting their capacities. The state sector slowed down after the first boom, while new private businesses joined the market and grew their market share. However, a more thorough analysis would be more instructive. Biofertilizers have not grown steadily over time, and their distribution and adoption rates both declined in the late 1990s. One would have anticipated a quicker and potentially faster growth performance as the input gains more acceptability after starting from a modest basis. Second, despite the increasing number of new entrants, the industry's average capacity decreased, resulting in a high number of small units. Size modification is common in the baby industry, but it's important to remember that distributing an agro-input also requires extensive sales networking and a thorough comprehension of agricultural field realities (Ghosh, 2004). Whether the smaller groups will be able to meet agricultural demands, work with larger producers, or just act as local bodies or distribution agents depends on whether they have the necessary skills and motivation. Despite the federal government's attempts, the technology has hardly been spread, and its distribution among units has changed to become more concentrated, particularly in Maharashtra and other western and southern states.

With differing levels of emphasis, the Indian government and the several state governments have been encouraging the use of biofertilizers through grants, extensions, and sales subsidies (Alam, 2020). As time passes, farmers' perceptions of the technology are shaped by the agronomic realities of their respective regions, the experiences of other farmers, including themselves, and the information provided by various disseminating agents. They then make their own adoption decisions (Khan et al., 2011c). The National Biofertilizers Development Centre Act Ghaziabad is offered by the Government of India, with six regional facilities located in Bangalore, Bhubaneswar, Jabalpur, Imphal, Nagpur, and Hisar. This can aid in comprehending the development of the technology and its uptake in India in the lack of published data on input usage at the farm level.

Successful Biofertilizer Implementation Case Studies:

1. A significant number of multilocational nodulation studies were conducted in the field in different districts of Tamil Nadu by the Biofertilizer Research Station at Tamil Nadu Agriculture University. Individual or combined applications of Rhizobium, Azospirillum, and VAM cultures were made, together with an appropriate dosage of inorganic fertiliser. The land was in a variety of situations, including dry and irrigated, sandy loams to heavy clays, low to high nitrogen status, cotton, sesame, black gramme, groundnuts, sugar beetroot, paddy, and millets. In each case, the beneficial effects of these biofertilizers with only a portion of the recommended dose of inorganic nitrogen have been documented, as have the outcomes of establishing appropriate strains as inocula and their integration with combinations involving Rhizobium, Azospirillum, and VAM—individually, in combinations, or all together (Balasubramani & Vincent, 2021).

3. CASE STUDIES OF SUCCESSFUL BIO-FERTILIZER IMPLEMENTATION

1. Tamil Nadu - Multilocational Trials With Bio-fertilizers: The Biofertilizer Research Station at Tamil Nadu Agriculture University carried out a large number of multilocational nodulation trials in the field in various districts of Tamil Nadu. Rhizobium, Azospirillum, and VAM cultures were applied individually or in combination, and a suitable inorganic fertilizer dose was also applied. The land was under varied

conditions such as dry and irrigated, sandy loams to heavy clays, low in nitrogen to high nitrogen status, paddy, millets, pulses, groundnut, sugar beet, cotton, sesame, black gram, etc. The results of establishing suitable strains as inocula and their integration with combinations involving Rhizobium, Azospirillum, and VAM—singly, in combinations, or all together—and the useful effect of these bio-fertilizers with only part recommendation dose of inorganic nitrogen in each case have been reported (Balasubramani & Vincent, 2021).

2. Case Studies of Bio-fertilizer Application (Field Adoption) from Tamil Nadu: The doyenne of phosphatic bio-fertilizer research in Tamil Nadu detailed the field investigations on the impact of phosphobacterization, which were tried out in potato, sorghum, maize, cotton, rice, and sesame without or against the recommended dose of phosphorus. The experiments were conducted in varied soils from red loamy, mixed red and black soils to sandy soils of Tamil Nadu, and all led to increased yield and more economic profit than chemical inoculation. Inputs on effective culturing and customization of inoculants, seedling seeding rate, cost and benefits of technology dissemination in developing countries, and effective training for transferring technology were also recommended to further explore this direction. Phosphorus solubilizing and nitrogen-fixing bio-fertilizer cultures, both in single and composite formulations, were tried out in both red and black soils. Host crops like sorghum, red gram, groundnut, bajra, rice, small millets, and pulses like cowpea, field beans, and vegetable crops were sown. Bacterial bio-fertilizer was also mixed with seeds, and broadcasting in the field was also done to maintain the randomized block design. The results showed a resultant increase in nodulation, grain, and straw yield in the host plants, as well as soil nutrient status at the end of two years (Elnahal et al.2022).

4. ADVANTAGES AND DISADVANTAGES OF BIO-FERTILIZERS

Bio-fertilizers can be used along with chemical fertilizers in order to optimize the nutrient use efficiency and avoid environmental contamination caused by the addition of excess chemical fertilizers to the soil. Various benefits are associated with the use of bio-fertilizers. Inoculation of beneficial microorganisms through bio-fertilizers can enhance and maintain soil health, form symbiotic associations with plant roots, and supply essential plant nutrients at different growth stages. They promote the growth of plants by mobilizing nutrients and increasing their availability through direct or indirect processes or mechanisms, solubilization followed by sequestration and co-precipitation, which are also in accord with the various rhizospheric processes. In addition, bio-fertilizers are environmentally friendly, biodegradable, and replenishable due to continuous microbial multiplication. In many situations, bio-fertilizers can serve as an alternative for or a supplement to energy-intensive chemical fertilizers and can also play an important role in sustainable agricultural production by minimizing the environmental issues occurring due to their overuse. However, there are disadvantages in the usage of bio-fertilizers. They slow down the rate of nutrient release into the soil when compared to chemical fertilizers in general. The use of bio-fertilizers tends to impart balanced nutrition to the plants as there is a slow and steady supply of nutrients. Releasing the nutrients at the appropriate time according to the plant requirements is important for profitability. Farmers do report better yields post the usage of bio-fertilizers, but the increase in yield is not as high as that derived from the usage of chemical fertilizers. Therefore, a balanced view needs to be taken by the farmer before deciding upon the usage of bio-fertilizers.

The introduction of bio-fertilizers as an assistant to soil health is in alignment with the agenda for the restoration and enhancement of soil fertility. The application of bio-fertilizers reduces the dependency on synthetic fertilizers, leading to the development of sustainable agricultural practices. In addition to its conserved microbial diversity, this alternative facilitator of soil health is equipped with a superior approach in terms of improving soil structure. It can contribute to the detoxification of chemicals, minimize soil erosion and pollution by enhancing the aerial vitality of plants developed through organic systems. The application of bio-fertilizers increases microbial diversity in agricultural field sites, especially in certain intriguing crops, and cannot combat crop inlet and disease judiciously in the absence of bio-fertilizer application.

There have been many studies reporting a significant soil microbial response to bio-fertilizers, especially bacteria. Further studies have stated that soil structural compounds such as soil colloids and dead plants lead to an increase in nutrient acidity that improves the composition of soil microbial communities. Additionally, bio-fertilizers support the enhancement of nutrient cycling through the creation of the soil ecosystem. Today, the emphasis is on sustainable management of organic and inorganic resources at the optimal level of applied nutritional value, only to maintain soil health, increase soil organic matter, and enhance abiotic and biotic stress protection of crops. Efforts are underway to develop and improve agriculture by harmoniously encompassing various and diverse principles. Bio-fertilizers are bacterial agents that have biological roles in a house's ability to deter disease, alleviate biotic stress symptoms, and facilitate biotic strain controls.

5. CONCLUSION

It is important to support the novel application methods, especially the use of methylcellulose for seed coating and pellets for direct soil application. Responses typically rely on a number of environmental elements. (1) The response is influenced by the kind of soil as determined by its water-holding capacity, alkalinity, salinity, and acidity, as well as the amounts of other nitrates, phosphate, and even calcium and molybdenum that aid in Rhyzobia protein synthesis.

A higher starting dose of the mineral N-suppresses nodulation, which lowers the responsiveness of a phosphate but rhyzobium shortage may also act as an inhibitor. (2) Nonsymbiotic strains, which primarily rely on soil organic matter for energy, are more discouraged by the lack of organic matter, which is particularly prevalent in dryland and agricultural environments. Only soils with limited accessible phosphorus and a high organic content showed a positive phosphobactrin reaction. (3) Two major abiotic factors influencing N-fixation on dry land are a lack of water in the soil and high temperatures farming. (4) The inoculants are opposed by the native microbial community. Predatory organisms, which are frequently already found in the soil, are generally better suited to their surroundings and outcompete the injected population.

6. FUTURE PROSPECTS AND OPPORTUNITIES FOR BIO-FERTILIZERS IN INDIAN AGRICULTURE

Future prospects for bio-fertilizers are positive for two main reasons. The first is linked to a growing international trend in recent times for moving towards organic or natural sources of nutrient supply, rooted in a growing public awareness about the environment, biodiversity, conservation of human and animal species, and sustainable living. The second reason leverages the renewed appreciation and understanding of the importance and role of bio-fertilizers by various stakeholders in various locations and on different local cropping systems. We also think that India, like many other developed and developing nations, needs long-overdue reforms in its policies and investment models for research that focuses on society, the environment, and zero hunger goals, and not just rapid and large-scale production of food grains. Similarly, more useful and location-specific agro-ecological quantification of the efficiency of bio-fertilizers in the Indian agro-ecosystem shall be key for policy decisions regarding bio-fertilizer development.

India will require more investments for its bio-fertilizer development, including the construction of microbial gene manipulation facilities for novel bacteria or fungi suited to Indian soils and climates, and application strategies through crop residue management that may suit Indian farmers. Other focus areas should include investments in and incentives for sun-ranging, ground-truthing research and data collection, done less within laboratories and experiment stations but at times on farmers' fields, that can assess the contact effect of biological nitrogen fixation and bio-fertilizers in non-directly affected crop types and provide new insights into future research. An alliance of farmers, producer houses, civil society, policymakers, funding agencies, processors, and most importantly, academicians and scientists shall collectively work on future advances for bio-fertilizer application, such as opportunities for improving shelf life, understanding the compatibility of multi-microbe interactions within several agro-ecological landscapes, delivering innovation for reaching resource-poor farmers, and also public education around the risks and reasons for bio-fertilizer technology for sustainable agriculture. Revolutionary technologies like precision farming, coupled with knowledge of soil and agronomy, could also provide benefits of using bio-fertilizers.

With the advancement of technology, the future of bio-fertilizers appears to be quite promising. In the development of new and better bio-formulations, bioinformatics plays a pivotal role. It can provide insight into the intricate molecular cross-talk that takes place during the co-inoculation of various microbial strains. In this era of synthetic biology, it is quite simple to modify a microbial strain with the desired characteristics. By employing precision farming technology in combination with bio-fertilizers, one can achieve high efficiency with a minimal associated risk. A considerable amount of money and human resources should be spent on technological research to unlock the sea of potential opportunities of bio-formulations. The possible areas of investment in terms of technological research include biotechnology, microbiology, and bioinformatics, among others. With the help of bioinformatics software and hardware, researchers and bio-formulation developers can better visualize how different strains interact with each other. User-friendly applications can be developed for the farmer community that can be operated using mobile phones and will be very low-cost. These applications will contain all the relevant instructions for utilizing the bio-fertilizers directly by the farmers.

An array of new technological advancements in the field of agriculture has potential uses with fertilizers or the plant-microbiome, including systems biology, metabolomics, bioinformatics, chemistry, polygenomics, genomics, systems genetics, synthetic biology, gene editing tools, and plant genetic modifications. Probiotics and smart fertilizers for plant microbiome management form the underpinning of our current and future work and opportunities. Herein, we outline ways these can be taken forward further. To effectively make discoveries, systems studies of the microbiome and of microbial and plant genomics should be integrated into plant breeding. Plant-microbe studies are yielding not only prospects for new probes, pest control methods, probiotics, or direct inoculants, but also creating paradigm shifts about what is possible in agriculture and environmental science, considering precision agriculture, bio-resilience testing, and replacements for chemical pesticides and fertilizers.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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