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From Soil to Harvest: Evaluating Bio-fertilizers in Enhancing Organic Farming and Sustainable Agriculture

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Abstract: *This review paper explores the critical role of biofertilizers in enhancing sustainable agricultural practices, particularly within organic farming systems. Agriculture, a field encompassing diverse practices from crop cultivation to livestock management, has evolved significantly since its Latin origins. Today, sustainable farming demands practices that not only ensure high-quality food production but also safeguard environmental and economic viability. Organic agriculture has seen substantial growth globally, driven by its perceived health benefits and environmental sustainability. Biofertilizers, which utilize beneficial microbes to improve soil health and nutrient availability, present a promising alternative to chemical fertilizers. They enhance soil fertility by fixing atmospheric nitrogen, solubilizing phosphorus, and promoting plant growth through natural processes. In India, where conventional farming faces challenges such as soil degradation and pollution, bio-fertilizers offer an eco-friendly solution that aligns with sustainable agricultural goals. Despite their benefits, the adoption of biofertilizers is hindered by issues such as storage sensitivity and formulation challenges. This paper discusses the current advancements in biofertilizer technology, their comparative advantages over chemical fertilizers, and the need for continued research to optimize their use and overcome existing limitations.*

Key words: bio-fertilizer, organic farming, chemical fertilizer, microorganisms, soil health

Introduction

Agriculture is the most comprehensive word used to denote the many ways in which crop plants and domestic animals sustain the global human population by providing food and other products (Harris & Fuller, 2014). A sustainable farm must produce sufficient quality food, manage its resources responsibly, and ensure environmental safety while remaining profitable. Rather than relying on commercial fertilizers, a sustainable farm seeks to maximize the use of advantageous natural processes and resources that originate from the farm itself (Reganold *et al.*, 1990).

Originating from the Latin words *ager* (field) and *colo* (cultivate), the English term agriculture means "field" or "land tillage" when combined. However, the term has come to consist of an extensive spectrum of essential agricultural activities that have their own descriptive terms, including horticulture, arboriculture, agriculture, domestication, cultivation, and forms of livestock management like pastoralist, transhumance, and mixed crop-livestock farming. Plus, terms like "a beginning," "proto," "shifting," "extensive" and "intensive" are commonly used to describe agriculture, yet it is not always clear what they exactly signify. Specific types of agriculture are also defined by a wide range of criteria (Harris & Fuller, 2014).

The Importance of Organic Farming in Today's Agriculture

The principles of organic farming revolve around promoting sustainability and diversity while targeting social, environmental, and economic aims. They combine various management techniques with fundamental tools that illustrate the appropriate ways to care for animals, supply them with shelter, and nourish them according to their individual requirements. Organic farming tends to be more lucrative due to its ability to command higher prices while maintaining lower variable expenses. They have more and different kinds of insects, birds, and plants, along with bigger and more varied groups of these living things. To promote environmentally sustainable farming practices, we can learn from organic agriculture, yet it is crucial to receive further support from lawmakers and increased investment in research (Stockdale *et al.*, 2001).

Around the world, organic agriculture (OA) has grown greatly, with sales of certified organic products (OPs) approaching 20–25% year⁻¹ since 1990. With OPs making up roughly 2% of the US market and 1% to 5% of the EU market, the global OP market is expected to be valued at \$20 billion in 2001. The increase of processed OPs has been tremendous, frequently exceeding 100% annually. The concept that OPs are healthier, tastier, and more environmentally friendly than traditional products is what fuels the desire for OA. In severe droughts, OA systems perform better than traditional agriculture and have much bigger gross margins, lower input costs, and higher input costs (Lotter, 2003).

Despite utilizing improved seeds and chemical fertilizers, India faces a significant hurdle in producing sufficient food for its rising population. Although organic agriculture has potential as a future option, issues related to soil health and contamination remains a concern. To encourage sustainable agriculture in northern India, India produces certified organic products, including food and various other items (Yadav *et al.*, 2013). In India, organic farming is a financially and environmentally sound way to produce food, ensure food security, and address environmental issues. The technique uses crop leftovers, green manures, animal manures, off-farm waste products, and bio-fertilizers, which together may provide 7.04 Mt of primary nutrients for India. By managing population increase, food grain output, nutrient consumption, and halting soil nutrient depletion, organic farming could potentially enhance food security. Further investigation is necessary in order to completely comprehend the availability of organic feed materials and contaminants in India. It is important to implement policies for accountable disposal of bio-waste, integrated farming practices, pest control, and supporting the domestic market for organic produce (Manna *et al.*, 2021).

Understanding Bio-fertilizers and Their Role in Organic Farming

- What is a bio-fertilizer?

Bio-fertilizers are compounds that are strengthened with microbes that aid in the growth of plants and tree tissue through supplying them with more vital nutrients.

Microorganism-based biofertilizers are vital for saving soil health because they release vital nutrients toward the soil through biological processes. Living inside the bodies of algae, bacterial species, and fungi, these natural fertilizers increase the total quantity of nutrients available to plants, especially with respect to the rising costs of chemical fertilizers and their detrimental effects on soil health (Kumar *et al.*, 2017).

Due to bound agricultural productivity, the increasing world population is a serious threat to food security. Chemical fertilizers are exceptionally risky for the environment and the health of people. Microorganism-based biofertilizers are an environmentally friendly option for chemical fertilizers, as they advertise plant growth and sexual reproduction. These biofertilizers are crucial for crop production sustainability, preserving soil fertility over the long term, and sustainable farming (Kumar *et al.*, 2018). By improving their accessibility of essential minerals through biological nitrogen fixation, phosphorus solubilization, and growth hormone creation, biofertilizers—living germs in plant roots—enhance growth, productivity, and physiological characteristics. More sustainable and improving soil health than synthetic fertilizers, these beneficial organic agro-inputs is somewhat an ideal choice. In addition to becoming quicker and more productive, biofertilizers also reduce the chances of pest and pathogen resistance (Mushtaq *et al.*, 2021).

Indian agriculture:

India's agriculture industry is essential to the country's economic expansion for it creates jobs, income for farmers, and makes certain food security. The extensive use of pesticides and fertilizers in conventional farming lowers soil fertility, contaminates rivers, and spreads disease. Due to its limitations, organic agriculture is emerging, with 1.59 million producers and 2.7 million hectares of cultivated land. This essay examines the background and present situation of organic farming in India, pointing out challenges that get along its trajectory and suggesting fresh approaches to development to encourage sustainable expansion (Avi and Batra, 2023).

India's development and progress depend heavily on organic farming, which aims to solve the growing problem of food security. Agriculture diversification is a top priority for the government, with horticulture, floriculture, aromatic and medicinal plants, beekeeping, and sericulture receiving special attention. To reach superior standards, there is still opportunity for technological and agri-infrastructure advancement. The need for farmland can be lessened and the detrimental effects of modern agriculture on the health of the community and the environment may be tackled by the role of organic farming in India's rural economy (Chandrashekar, 2010).

In the years following the Green Revolution, Indian agriculture faced struggles due to declining rates of productivity growth, shrinking soil fertility, and higher expenses for production. This puts nation-wide food security in compromise and brings up troubles with resource-poor farmers. New farming ideas that seek to restore agriculture to its previous basic state while advocating sustainability and ecologically friendly practices, such as organic farming, natural farming, biodynamic agriculture, eco-farming, and do-nothing agriculture, have been put into place in an effort to address these problems (Saini and Pandey, 2009).

Given its positive effects on the environment, economic growth, and human health, sustainable farming grows more and more popular with the general public. Conventional foods are dangerous because they contain dangerous ingredients like antibiotics and pesticides. One of the biggest producers in the world present-day is organic farming, which does away with synthetic pesticides and fertilizers. India has experienced a sharp increase in organic farming as a result of its native skill, ensuring sustainable growth and a healthier nation at large (Das *et al.*, 2020).



Types of Bio-fertilizers

N ₂ fixing Bio-fertilizers	
Free-living	Azotobacter, Beijerinckia, Clostridium, Klebsiella, Anabaena, Nostoc
Symbiotic	Rhizobium, Frankia, <i>Anabaena azollae</i>
Associative Symbiotic	Azospirillum
Phosphate solubilizing Bio-fertilizers	
Bacteria	<i>Bacillus megaterium</i> var. <i>phosphaticum</i> , <i>Bacillus subtilis</i> , <i>Bacillus circulans</i> , <i>Pseudomonas striata</i>
Fungi	<i>Penicillium</i> sp., <i>Aspergillus awamori</i>
P Mobilizing Bio-fertilizers	
Arbuscular mycorrhiza	<i>Glomus</i> sp., <i>Gigaspora</i> sp., <i>Acaulospora</i> sp., <i>Scutellospora</i> sp. & <i>Sclerocystis</i> sp.
Ectomycorrhiza	<i>Laccaria</i> sp., <i>Pisolithus</i> sp., <i>Boletus</i> sp., <i>Amanita</i> sp
Ericoid mycorrhizae	<i>Pezizella ericae</i>
Orchid mycorrhiza	<i>Rhizoctonia solani</i>
Bio-fertilizers for Micro nutrients	
Silicate and Zinc solubilizers	<i>Bacillus</i> sp.
Plant Growth Promoting Rhizobacteria	
<i>Pseudomonas</i>	<i>Pseudomonas fluorescens</i>

Table 1- Types of bio-fertilizer with microorganisms (Kumar *et al.*, 2017)**Benefits of Bio-fertilizers in Organic Farming**

India has historically used biofertilizer, an efficient, easy-to-use, and low-cost fertilizer. Traditional chemical fertilizers, which impact the environment and increase the risk of diseases like tumors, have been displaced by this kind of substance. Microorganisms found within biofertilizers provide the vegetative world the right nutrition, growth, and physiology. It is made possible by the association of living microorganisms that encourages flora reproduction and sustainable development. Organic farming relies heavily on biofertilizers since these substances improve soil fertility, stability, and reduce environmental impact—all of which ultimately protect lives and enhance ecosystems (Anuradha and Singh, 2021).

By improving the nutrient efficiency of mineral fertilizers and soil resources, bio-fertilizer contributes enormously to agricultural production on both a direct and indirect level. They encourage organic and environmentally conscious farming via providing plants vitamins, hormones, regulating and both natural and synthetic acids. Purified and organic agriculture depends on the cultivation of microorganisms and their metabolites that are not harmful to the environment. N₂ fixing, phosphate solubilizing, phosphate in the coordinating, and micronutrient-based biofertilizers are the different types of biofertilizers. Nitrogen-fixing

organism cultures, phosphate-solubilizing and -mobilising organism cultures, and plant growth-promoting rhizobacteria (PGPR) are the most vital types of biofertilizers used in agriculture. By competing with other microorganisms, creating allergenic substances that interfere with pathogenic organisms, and causing persistent resistance in plants, these kinds of bacteria encourage the establishment of plants. Although PGPR are crucial to naturally occurring and environmentally friendly agriculture, the kind of host plant they affect determines how they function (ZİNCİRCİOĞLU and YALÇIN, 2018).

Enhancing soil fertility and reducing the need for chemical fertilizers are two major goals of biofertilizers. They can raise grain yield alongside harvest index while also improving soil structure. A combination of Azotobacter, Rhizobium, and VAM inoculation maximizes wheat and grain yield. The microorganisms incorporated into commercially available biofertilizers help solubilize fixed micronutrients such as zinc as it re Modern disease management techniques like bio-control are of considerable potential application in agriculture. Certain plant growth, yield, and quality variables can be significantly enhanced by using biofertilizers that contain microbial strains, phosphate and potassium dissolving microorganisms and bacterial nitrate (Kapoor *et al.*, 2015).

Applying bio-fertilizers (N-fixers) greatly enhances the fertility of the soil and its yield-attributing properties, which raises the final yield. In temperate climates, rhizobium inoculation increases yield, seed pod volume, and capsules a particular number. BGA+ Azospirillum boosts yield attributes in low land circumstances. In acidic and alkaline soils, microbial inoculants serve as vital for getting back to successful microbial communities and making sure future crop yields (Goutami *et al.*, 2017).

Application and Sustainability

I. Seed Treatment

Before seeds are sown, chemical or biological agents are introduced to them with the aim to suppress pests, diseases, and insects. Improvements in technology like seed priming and fluid drilling have established a roadmap to enhancing existing treatments. Since biological seed treatments are safe for the environment and have encouraging socioeconomic consequences, they should be among the fastest-growing sectors in the near future. To enhance disease management, farmers should make an effort to implement these advances in technology (Sharma *et al.*, 2015).



II. Seedling root dip treatment

Before being transplanted in the field, the seedling roots of transplanted commodities are treated for 30 minutes in a biofertilizer solution. Applying this method, 2-3.5 kg of biological fertilizers is used to inoculate the seedlings needed for an acre. For this, a bucket with enough quantity of water is gathered and the biofertilizer is utilized well. The seedlings' roots are then dipped in this mixture to allow the roots to absorb the fungicide. After that, these seedlings are transplanted. It has been discovered that this technique works incredibly well for crops including flowers, rice, onions, tomatoes, and Cole crops.

The work offers a rhizosphere-based P management strategy to enhance rice seedlings' nutrition during transplantation by providing more phosphorus. The technique, which includes phosphate-solubilizing bacteria and root-dip planting of seedlings, performs better than conventional techniques in terms of root volume, P uptake, grain production, and fertilizer input quantity. Along with equivalent grain output and a 50% decrease in fertilizer input quantity, the approach also demonstrates better results. This method of controlling phosphorus in acid soils could be applied globally (Kalidas-Singh & Thakuria, 2018).

III. Soil application

Bring together PSM (Potassium, Magnesium, and Sulfur) with from 400 to 600 kg of FYM cow dung and, if available, ½ bag of rock phosphate. The PSM, cow dung, and rock phosphate mixture needs to be kept overnight in the shade or beneath a tree, with a humidity level of 50%. The mixture can be applied with the soil in rows or when leveling the surface of the earth.

It has been demonstrated that applying biofilm biofertilizer, a decomposed organic fertilizer, improves soil fertility and raises plant yield in Vertisol. Upland kale seeds and different amounts of organic fertilizer were juxtaposed in a field experiment. The best yields were found in 21 ton/ha organic fertilizer (76.5 ton/ha), but the ideal dosages were 15–18 tons/ha. Upland kale yields decreased when three metric tons of organic fertilizer per hectare was applied instead of fertilizer made with NPK (Sudadi *et al.*, 2020).

Microorganism inoculating agents, or biofertilizers, are crucial to environmentally conscious farming for controlling key nutrients like phosphorus and nitrogen. These biofertilizers improve the nutrition of legumes and non-legumes with regard to nitrogen and phosphorus. But in the circumstances of India, challenges like longevity and formulation methodology must be resolved in order to achieve considerable fertilizer savings (Brahmaprakash and Sahu, 2012).

A novel bio-fertilizer encapsulation methodology was created using humic acid to combine Chitosan, and alginate with nanocapsules that were stored with beneficial organisms and essential agro-nutrients (NPK). Analysis of the framework and morphology showed better performance rather than non-cross linked nanocapsules too. This technique reduces the detrimental impact on the environment and promotes plant growth by providing a controlled discharge of NPK and PGPRs for those who are environmentally conscious (Hamed *et al.*, 2024).

Comparing Bio-fertilizers with Chemical Fertilizers



Impact on Soil Health and Fertility	
Bio-fertilizers	Chemical Fertilizers
- The living or dormant cells of effective strains of microbial inoculants used in biofertilizers speed up the microbial process and increase the amount of nutrients that are easily taken in by plants. By developing nutritionally significant elements into forms that are easily available through biological processes consisting of nitrogen fixation and rock phosphate solubilization, they push growth. The goal of biofertilizers is to capitalise on the biological system of nutrient mobilization that is present naturally (Yadav and Sarkar, 2019). - The most advantageous and ecologically friendly method of providing integrated nourishment in agriculture; however considering their high sensitivity to changes in temperature and humidity, act less rapidly than chemical-based fertilizers, and should only be used in conjunction with other fertilizers (Yadav and Sarkar, 2019).	- Chemical fertilizers modify the properties of soil and elevate crop productivity encompass phosphate, potassium, and nitrogenous fertilizers. On the reverse, fraud may end in an overall reduction in soil organic matter (SOM), a minimization in soil quality, and environmental risks. Overuse may contaminate the air, water, and soil, harden the soil, and minimize fertility. In addition, it could decrease the total quantity of organic matter in the soil, weaken microbial activity, and attract more pests. This may block plant growth and increase greenhouse gas emissions, which will have negative impacts on the biodiversity of the soil (Pahalvi <i>et al.</i>, 2021). - The micro flora, soil, and human health are all negatively impacted by those chemicals over time and low sensitivity to changes in environment in comparison of bio-fertilizers (Baweja <i>et al.</i>, 2020).
Environmental and Ecological Effects	
- Microbes increase crop yield and plant biomass in both greenhouse and outdoors environments. Preparing the inoculums, cell protectants, carrier materials, and delivery methodologies are some of the recent advancements in biofertilizer formulations (Kumar <i>et al.</i>, 2022). - Examples of these communities include mycorrhizal fungi and <i>Azotobacter</i> sp. The function, plant-microbe interaction, and microbial adaptability are the environmental factors that affect the use of biofertilizer (Meena and Busi, 2019).	- Chemical stressors may result in harmful effects on aquatic species and ecosystem. Toxicants may cause lethal effects on organisms and environment (Connon <i>et al.</i>, 2012). - Production and portfolio diversification of chemical substances are transforming at greater speed than other change agents, particularly within developing nations (Bernhardt <i>et al.</i>, 2017). - Chemical fertilizers meet food security standards through stimulating plant growth, but they do not foster the growing of healthy root, shoot, or root systems, or nutritious plant characters. The harmful impacts of these chemicals accumulate up in the body, contributing to destruction of soil, water pollution, and air pollution (Kumar <i>et al.</i>, 2019).
Nutrient Management	

• Crop production is dependent on the availability of minerals, which include macro nutrients like nitrogen, phosphorus, potassium, and sulfur and micronutrients. In order to improve plant performance and show complementary effects to mineral fertilization, microbial-based bio-formulations are required (Bargaz <i>et al.</i>, 2018).	• The last 40 years witnessed a fifteen-fold increase in nutrients being applied at rates, which led to a significant increase in fertilizer consumption around the world. Crop nutrient recovery, however, is still low. To help to address these challenges, slow/controlled release fertilizers (SRF/CRF) balance nutrient release with plant demand and address the supply of nutrients in the plant-soil system (Shaviv and Mikkelsen, 1993).
Cost and Application	
• India produces biofertilizer on a pilot measure using impacts of Azotobacter and Rhizobium which concludes in a net annual benefit of \$6000. A great a chance for entrepreneurial activities in countryside alongside other countries that are developing, as indicated by the \$5000 cost of fabrication that comprises salary and wages (Sethi and Adhikary, 2012).	• India has gone through a green revolution because of chemical fertilizer, but there have been additional financial costs and soil damage. In order to preserve crop yield and defend farmers' incomes, equilibrium of chemical fertilizers and organic manure is necessary (Ghosh, 2004).

Advantages and Challenges of Using Bio-fertilizers

A sustainable substitute for synthetic fertilizers, biofertilizer increases agricultural produce yields through lithosphere preservation, biosphere enhancement, and decreased soil pollution. In addition to releasing plant growth regulators while supplementing soil with macro- and micronutrients, it also helps vegetables oppose illness and stress. "Nitragin" was the first bio-fertilizer to be sold for business in 1895. The research and production of genetically engineered and mutant microbes for environmentally friendly agriculture should be the primary priority in the future (Chakraborty and Akhtar, 2021).

In order to support a coordinated nutrient management strategy, biofertilizers can produce vegetation with values similar to those of mineral fertilizers while requiring a far smaller proportion of fertilizer (Malusà *et al.*, 2016). Biofertilizers work by using atmospheric nitrogen and enhancing the amount of phosphorus content of soil over time. By transforming exacerbated nutrients into less complicated ones and manufacturing growth-promoting hormones, they encourage root proliferation. Microorganisms ensure that plants grow and regulate themselves properly, breaking down convoluted nutrients into simpler ones. Biofertilizers shield plants from diseases transmitted by the soil and boost crop yields by 10% to 25%. They guarantee that plants grow and are regulated properly, and they are both cost-effective and good for the environment (Kumar *et al.*, 2017).

The creation of smart nano-fertilizers, which blend traditional fertilizers and nano-nutrients, is an outcome of recent uses of nanotechnology in soil management. However, concerns about eco-toxicity and toxic effects have contributed to consumer appetite for replacement. The most practical improvement is nano-biofertilizers, a conjugate preparation which incorporates soil-beneficial microorganisms with nano- and bio-fertilizers to improve the production of crops, address environmental reverence, and uphold sustainable practices (Kalia and Kaur, 2019).

Challenges of Biofertilizers

Microbial-based fertilizers created by soil microorganisms might improve the development of plants. However, there are obstacles to their use in agriculture, including scarcity of clarity about how they interact with plants, uncertainty, and difficulty identifying and tracking inoculation strains. The extraction method, the endurance and traceability of inoculants, and farmer behaviors are all factors that impact the effectiveness of biofertilizer (Malusà *et al.*, 2016).

It was discovered that the use of *Azospirillum* and *Azotobacter* in Haryana Agricultural University, Hisar, had significant impacts on the nutrient content, growth, and yield of the flowering *Chrysanthemum* plants. The maximum fresh weight and flower yield per plant have been proven by the combination of *Azospirillum* and nitrogen, while the highest nitrogen content has been shown by the combination of *Azotobacter* and nitrogen. On the percentages of potassium and phosphorus, however, the interaction effect was not significant. The study emphasizes how crucial it is to take consideration of how nitrogen and biofertilizers interact to impact growth of plants and work efficiency (Kumari *et al.*, 2014).

The act of nitrogen fixation, which converts molecular nitrogen into the gas ammonia, serves as crucial to plant growth. As a rising number of nitrogen-fixing bacterial species infiltrate the rhizosphere, they interact with plants to fix nitrogen in terms of biology, produce phytohormones, reduce environmental stress, stop plants compared to creating ethylene, and enhance nutrient availability via the manufacture of siderophores (Bhat, *et al.*, 2015).

Plant growth regulators, which directly affect the hormonal circumstances of the plant, have been utilized in modern agriculture. These regulators, which include hormones, blockers, and inhibitors, manage numerous aspects of plant developmental processes, including senescence, blossoming fruiting, dormancy breaking, and the sprouting of seeds. They enhance crop management less difficult, boost yield, and extend shelf life and storage. These regulators were first commonplace in the 1930s, and their yearly global sales currently reach a total of \$1.2 billion (Rademacher, 2015).

Conclusion

Modern agriculture faces challenges due to the degraded soil fertility caused by chemical fertilizers, leading to health and environmental hazards such as soil erosion, water contamination, pesticide poisoning, and depletion of biodiversity. Biofertilizers, which naturally activate microorganisms in soil, are becoming increasingly important for crop production, restoring soil's natural fertility and protecting against drought and soil diseases. However, further research and development are needed to understand the mechanisms of action of various biofertilizers and find more competent rhizobacterial strains and carrier materials. Bio-fertilizers are essential components of organic farming, playing a vital role in maintaining long-term soil fertility and sustainability by fixing atmospheric nitrogen, mobilizing fixed macro and micro nutrients, and converting insoluble P into forms available to plants. Excessive reliance on chemical fertilizers is not a viable strategy in the long run due to the cost and environmental impact of setting up fertilizer plants and sustaining production. Organic manures (biofertilizers) could be a viable option for farmers to increase productivity per unit area.

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