Biofertilizers for Sustainable Agriculture: To Promote Healthy Soil and Food Security

LWS 548

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Executive summary

Several management practices of industrial agriculture, including the over application of pesticides and chemical fertilizers, contribute to the degradation of soils and the degradation of land at a global scale. The result is a reduction in soil fertility, which in turn has led to a decrease in both the quantity and quality of crop production. With the ever-increasing demand for food to feed a growing world population, there is a critical need to support access to nutritious, culturally appropriate, and economically viable foods, while enhancing the soil health of our agroecosystems. The use of alternative practices in agricultural production has proven to provide a potential solution to the problems associated with soil degradation. Alternative agricultural practices are adopted as an approach to promote healthier soils and to provide farmers with more productive and higher quality crops. As alternative management practices improve soil health, the adoption of biofertilizers, offer a sustainable alternative to enhance soil health and achieve higher agricultural productivity. This paper informs and communicate with farmers and government officials the wide adoption of biofertilizers as an alternative to synthetic fertilizers, therefore reducing the environmental impacts related to synthetic fertilizers, while enhancing global food security.

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1. Introduction

1.1 Background

The growth in global population has resulted in a global concern of food security, which has resulted in a higher demand for food. The global food security issue, therefore, poses a significant challenge to achieving the sustainable development goal of zero hunger (Albu, 2021). Besides the ever-increasing demand for food, and that arable lands is a limited resource has increased the challenge. Over the period 1961 to 2016, the global area of cropland per capita has experienced a continuously decreasing trend from about 0.45 hectares per capita to 0.21 hectares per capita during the period from 1961to 2016 (FAO,2020). Therefore, the primary goal of meeting food and nutritional needs throughout the world is to improve and maintain agricultural crop yields without posing negative impacts on the environment.

The traditional approach to addressing food issues was production-driven, focusing on boosting food supplies to influence food security directly by the application of chemical amendments , without taking into account the importance of other aspects of the food system. The adverse effects of chemical inputs on ecosystem are increasingly being recognized, including contamination of soil and waters, destruction of soil microbial communities, reduced soil fertility, and a greater vulnerability to crop diseases (Kremsa, V. Š. ,2021). In addition, the application of chemical fertilizers has negatively affected soil health. Intensive chemical fertilizer application result in excess nutrients either persisting for a long time in the soil or leaching out into nearby water environments (Bisht et al,2020). The factors that determining soil health, such as soil biodiversity and organic matter content are decreasing and resulting in soil degradation (Lal,2015).

The use of alternative practices in agricultural production has suggested to provide a potential solution to the problems associated with soil degradation. A system of agriculture that does not use conventional methods of production is referred to as alternative agriculture (Kremsa, V. Š. ,2021). The aim of alternative agriculture systems is to achieve sustainable performance by maximizing all elements of the agroecosystem. In addition, it seeks to reduce or eliminate the use of chemical fertilizers and to mimic natural cycle by using crop rotations, cover crops, and no-till farming techniques. Plant nutrition and soil health can be improved with alternative agricultural systems, particularly using beneficial microorganisms (Lal,2015). Thus, these alternatives offer an affordable, sustainable, and long-term approach to reduce chemical inputs, which enable farmers to facilitate the movement toward global food security.

1.1.1 The intensification of agricultural production and its negative impacts

Soils have lost their ability to provide many ecosystem services due to human use of soils, including intensified agricultural production for food security(Kopittke et al.,2019). 33% of soils have been moderately to severely degraded by soil erosion or contamination and over 52% of agricultural land has already experienced negative impacts brought by soil degradation at a global scale (ELD, 2015).Additionally, it has been predicted that, over the next 25 years, land degradation might result in a decline of 12% in world food productivity and an increase of 30% in food prices (ELD, 2015). Particularly, the application of synthetic fertilizers is playing an important role in the current intensification of agricultural production. According to historical estimates, an increase in crop productivity is partially attributed to the application of nitrate fertilizers (Stewart et al., 2005). Presently, the world produces 123 Tg of nitrogen fertilizer annually, representing an increase of 9.5 times since 1961 (FAO,2014). While N fertilizer is responsible for the majority of the food production, efficiency has decreased greatly in proportion to the amount of their use. For example, when global cereal yields and global N fertilizer yields are compared, it was discovered that the most efficient way to increase yield is to use N fertilizer at the lowest rate, which means that the efficiency decreases as the N fertilizer rate increases. Similarly, the efficiency of nitrogen use has also declined from 68% in 1961 to 47% in 2010, which means that only approximately 50%of the nitrogen fertilizer is absorbed by plants, whereas the remainder is being wasted (Kopittke et al.,2019).

A poorly managed fertilizer application is not only economically unfavorable, it has significant detrimental effects on the earth's soil and the environment as a whole. Firstly, the prolonged use of chemical based technologies has contributed to the degradation of soil quality, which has adversely affected its ability to support sustainable plant growth and crop production. For example, as a result of over-fertilization and subsequent leaching of nitrogen fertilizations in excess of plant requirements, soils become acidic. A global average of 0.26 units has been lost due to nitrogen addition to soils, and problems associated with acidic soils have emerged(Dashuan and Shuli, 2015). Moreover, by mining nutrient continuously while using chemical fertilizer, the soil becomes hungrier and becomes unsustainable as the gap between depletion and replenishment continuously builds (Kopittke et al.,2019).Excessive application of chemicals has led to soil degradation and wider ecosystem damage. Therefore, A more comprehensive decision-making process is needed that explicitly examines the trade-offs between intensifying agricultural production and reducing the value of other services.

1.2. Introduction to soil health

1.2.1. Definition of soil health

Soil health is defined by the US Department of Agriculture, (1997) as "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health". The importance of soil health goes way beyond an emphasis on crop production or other explicit interests of humans. The multidimensional nature of the soil health concept contributes to provide a basis for considering many stakeholders, functions and spatial or temporal scales regarding soil management objectives while aligning soil management goals with sustainable development goals(Lehmann et al.,2020).

Soil health is determined by the physical condition of the soil, such as its degree of compaction, amount of water stored, and its drainage(Magdoff, 2001). Growth of plants is negatively impacted by insufficient aeration, water availability, and soil strength. For example, crops growing on compacted soils often experience more adverse effects from both wet and dry weather conditions compared to crops growing in soils with a good structure (Magdoff, 2001). Compacted soils are insufficiently aerated during wet periods, and, given the conditions, they dry out more rapidly, forming a physical barrier that prevents roots from growing. In terms of the chemical factors, soil health can be determined by factors such as the level of nutrients, pH, salt content, etc. Lack of nutrients, high levels of a toxic element (such as Al), or high salt concentrations can all adversely affect plant growth(Magdoff, 2001).As mentioned, soil physical structure also affect soil health conditions. Generally, soils with few large pores, such as a very compact soil, are less hospitable to organisms including springtails, mites, or earthworms. Additionally, the lower levels of oxygen in compacted soils may also affect the form of nutrient available and its availability to the plants.

1.2.2.Factors contributing to soil health

The biological, chemical, and physical aspects of soil are all interconnected and affect one another (Magdoff, 2001). Therefore, it is difficult to identify any single practice or even a group of practices that are vitally important. However, soil microbial content is recognized to be crucial for soil health due to their profound effect on many soil properties. The structure, composition, and productivity of soil is affected by the soil microorganisms because of their sensitivity and reactivity to mitigate abiotic stress(Tahat,2020).Plant productivity has been shown to be corelated to underground biodiversity under a variety of environmental conditions(Wagg et al, 2011).

Biologically beneficial microorganisms are able to improving plant nutrition by– stimulating plant growth through direct or indirect mechanisms (Tahat,2020). For example, rhizosphere microorganisms inhibit pathogen growth by multiple mechanisms and promote plant growth (Tahat,2020).These mechanisms include promoting the uptake and utilization of nutrients by plants, increasing the plants productivity, production and activating antibiosis or causing systemic resistance and parasitism on soil farms, through selective uptake of Fe and P in order to combat soil-borne pathogens(Schnitzer et al, 2011).There are several rhizosphere organisms known to have beneficial effects on plants, including nitrogen-fixing bacteria, mycorrhizal fungi, plant growth-promoting rhizobacteria (PGPR), biocontrol microbes and protozoa (Tahat,2020). Every group contributes to enhance soil health and promote the development of sustainable agriculture(Figure 1).

The concepts of the significance of beneficial soil microorganisms in promoting soil health and sustainable agriculture

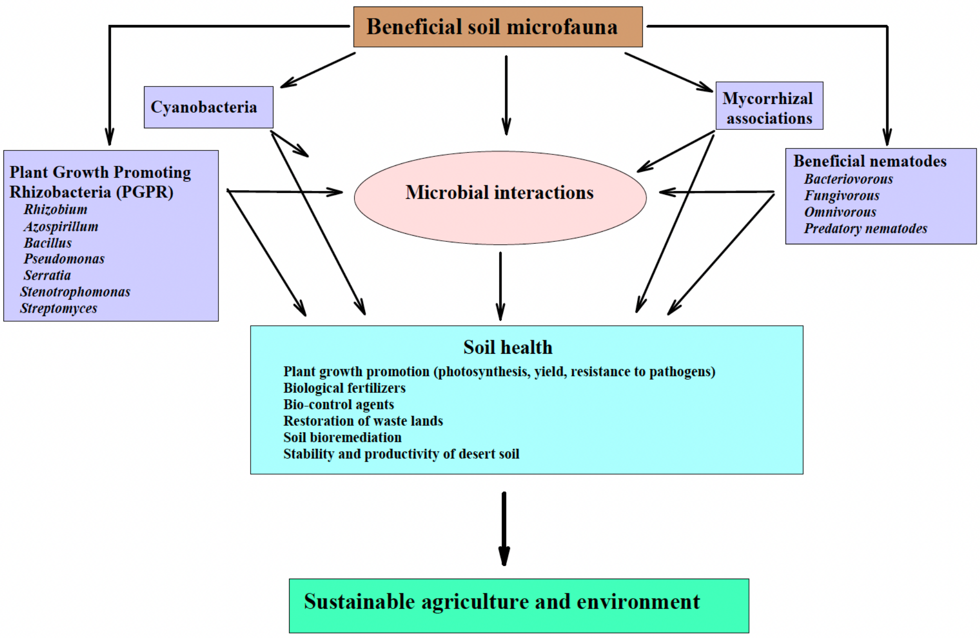

Figure 1(Adapted from Tahat,2020).

1.2.3. soil health and sustainable agriculture

Agriculture sustainability refers to the ability to carry out farming for future generations(Action and Gregorich,1995). With this long-term approach, agricultural production can be more efficient while simultaneously protecting the earth's natural resources. A vital link between sustainable agriculture and farming practices is the health of agricultural soils (Action and Gregorich,1995). For example, there are many agricultural practices that seriously reduce soil quality and harm the goal of sustainable agriculture, including soil erosion, contamination, soil biodiversity loss and unbalanced water resources (Action and Gregorich,1995). Such practices significantly reduce soil quality and undermine food security. Alternatively, by restoring soil health with appropriate farming methods, and maintaining or improving soil health, sustainable agriculture would be possible.

1.3. Introduce to alternative agriculture systems

Kremsa defined alternative agriculture as “the production of food that does not follow conventional methods" and the main objective of alternative agriculture is to follow agroecological principles, and optimize all agroecosystem resources in order to achieve sustainable performance(Kremsa,2021).There are a variety of alternative agricultural systems that emphasize management practices that mimic the physiological processes of nature (such as nutrient cycling, nitrogen fixation, and pest-predator interactions) to maximize land productivity while enhancing natural resource conservation including water, energy and soil (Kremsa,2021). Furthermore, they work to reduce or minimize the use of chemical fertilizers and chemical pesticides through the adoption of biological approaches, organic fertilizers, and organic amendments. Therefore, alternative farming provides a management framework for farmers to gain profit while respecting the environment.

1.3.1 Benefits of alternative agriculture practices

Alternative agricultural systems of farming has been shown to be more cost effective than conventional methods of farming by eliminating the application of mineral fertilizers and pesticides, minimizing soil erosion, and increasing the yields of crops (Faeth et al., 1991). With the process of transitioning from conventional agriculture to alternative agriculture, it has been shown that overall environmental and health problems have been reduced as a result of proper management and application of less synthetic fertilizers and pesticides. In terms of health, social and ecological aspects, both farmers and the public benefit from the minimal use of pesticides and chemicals in agriculture.

It has been shown that alternative agriculture would benefit waterbodies by using fewer chemicals on crops. According to the US Environmental Protection Agency (EPA), agricultural run-off is one of the major causes of non-point source pollution of lakes and streams. Each year, thousands of pounds of pesticide are applied to row crops and about five percent of the pesticides reach bodies of water and these water sources might be used for human consumption(EPA,1991). Surface water usually has a higher concentration of pesticides in its composition than ground water. According to a study conducted in Iowa, areas of intensive agricultural production had detected pesticide residues in all surface water sources, with nearly 73% of the samples are detected to contain several pesticides residues(Bane,1991). Furthermore, It has been estimated that 46 percent of all counties in the United States, contain groundwater that could potentially become contaminated by chemicals such as fertilizers and pesticides (Bane,1991).The public would have cleaner drinking water if the application of pesticides and fertilizers were lower.

Apart from providing clean drinking water, alternative agriculture also improves agricultural soil productivity. The combination of these factors results in reduced soil productivity. Studies have suggested that rotational cropping systems that include legumes would lose less soil nitrogen than continuous cropping systems (Bane,1991). A recent long-period research study also concludes that soil nitrogen is depleted more slowly through alternative cropping practices than by conventional methods(Faeth et al., 1991).

2.0 project objectives

The main objective of this report was "to assess and evaluate the adoption of biofertilizer as a potential alternative approach in agriculture systems for sustainable agriculture. The main focus was addressing the following to :

1. Conduct a review of the benefits and action mechanisms of biofertilizers.
2. Quantify the impacts of biofertilizers on crop yields and nutrient utilization efficiency.
3. Conduct an overview of the of global biofertilizers industry with an emphasis on Asian countries.
4. Identify challenges that threaten the wider application of biofertilizers and recommendations.

3.0 Study review

3.1.1 Definition of biofertilizers and their importance

Globally, biofertilizers have become increasingly popular over the last few decades due to widespread environmental degradation caused by the overuse of chemical fertilizers The widely accepted definition provided by Vesey (2003) defines biofertilizers as "a substance which contains living microorganisms which, when applied to seed, plant surfaces, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant." In contrast to synthetic chemical fertilizers, biofertilizers are a viable and sustainable biotechnological alternative that has proven highly effective in increasing crop yield, improving and restoring soil fertility, stimulating plant growth, and reducing the adverse impact on the environment (Atieno et al.,2020). Hence, As alternatives to chemical fertilizers, biofertilizers may be used to contribute to sustainable crop production and enhance environmental health.

Undoubtedly fertilizers are used indiscriminately as the food demand growth, which is making microbial habitats more vulnerable to pollution and degradation. Furthermore, as a result of using excessive chemicals, the crops have become more susceptible to disease, and the soil has become less fertile (Aktar et al. 2009). It was predicted that by 2020, the world's population would reach 8 billion and the amount of food grain required would be 321 million tons, but the available amount of nutrients will provide only for an estimated 21.6 million tons, creating a shortfall of approximately 7.2 million tons (Arun 2007). For a sustainable and environmentally-friendly way to feed a growing population and meet the nutrition requirements, agricultural productivity must increase significantly. Consequently, it is unavoidable that many existing agricultural methods must be reevaluated including the application of chemical fertilizers and pesticides etc. (Pretty and Bharucha 2015).

Biofertilizers may be a safer alternative to chemical fertilizers, since they do not have the adverse effects of chemical fertilizers and result in a lesser environmental damage.

A prolonged use biofertilizers could increase soil fertility significantly since they are cost-effective, eco-friendly, and eco-friendly in nature (Mahanty,2017). The soil ecosystem is composed of micro-organisms, which contributes to improve biological activity, allowing the soil to mobilize nutrients to support crop growth enables soil sustainability. Microorganisms in biofertilizers provide a number of benefits, including the provision of inexpensive source of nutrients, growth hormone secretion, micronutrient supply, as well as the ability to counteract the adverse impacts of chemical fertilizers((Atieno et al.,2020).

3.1.2 Action mechanism of biofertilizer

The rhizosphere is the region that is surrounding plant roots that contains a variety of microorganisms (Fasusi et al, 2021). Rhizospheres have a high microbial density and a high nutrient exchange capacity. There are various factors that contribute to the microbial biodiversity of the rhizosphere, including the architecture of root systems, the order of root branching and organic nutrients exuded (Fasusi et al, 2021). Therefore, in the context of rhizosphere management, the main goal is to increase the soil nutrient-use efficiency to maximize plant health and yield.

Several soil microorganisms(mycorrhiza fungi, plant growth-promoting rhizobacteria (PGPR)etc.) support plant rhizosphere management through multiple mechanisms(Fasusi et al, 2021).Nitrogen as an essential nutrient that is crucial for plant development, the nitrogen fixation process is necessary for plants to use nitrogen.A biological nitrogen fixation system can reduce emissions of greenhouse gasses, nitrogen losses, and fossil fuel consumption at the same time, thereby improving the long-term health and quality of soil(Fasusi et al, 2021). There are various nitrogen-fixing microorganisms that live on the root surface of plants and they are known as symbiotic nitrogen fixers. For example, rhizobium which is found in the root nodule of leguminous plants, allow nitrogen to be fixed from the atmosphere(Fasusi et al, 2021).

3.1.3. Biofertilizer application in agriculture.

There is a huge potential for biofertilizer in agriculture to sustain and improve the yield of different crops, including legumes, fruits, vegetables and forest products. Biofertilizers are proven to improve crop productivity in numerous studies worldwide (Table1) Plants benefit from biofertilizers in several ways. They fix nitrogen more efficiently, mineralize nutrients, release bound nutrients, and produce phytohormones, which protect plants from external stresses (Zakeel and Safeena, 2019). Using biofertilizers in cereals and legumes reaps more benefits since they increase the content of minerals, proteins, and amino acids, as well as improving their economic and nutritional value(Gautam et al., 2021).Similarly, biofertilizer has also been proven to enhance the productivity of vegetables, commercial flower crops, and fruit crops(Gautam et al., 2021). For example, a long history of successful use of biofertilizers in agriculture has been attributed to the inoculation of legumes with

Rhizobia. The symbiotic relationship between Rhizobia and legumes allows Rhizobia to fix atmospheric nitrogen (Atieno et al.,2020).

Biofertilizers are applied in the production of various agricultural crops.

Crop	Biofertilizer	Increase in yield	References
Cereals			
Triticum aestivum L.	*Azotobacter*	3.44 to 5.17 tons per 4200 m^2	Mohamed et al. (2019)
Oryza sativa L.	75% N + *Trichoderma* + *Azospirillum*	Grain yield increased from 20.87 to 40.07 g/plant	Khan (2018)
Setaria italica L.	*Rhizobium spp.*	Grain weight increased from 7.55 to 13.31 g per plant	Khatri et al. (2016)
Zea mays L.	*Pseudomonas* spp., *Saccharomyces* spp., *Bacillus subtilis,* and *Lactobacillus* spp.	Grain yield increased from 4.45 to 8.60 tons/ha	Kumar et al. (2019)
Legumes			
Cicer arietinum L.	Nitragin + biosuper	32% more grain yield than control	Rabieyan et al. (2011)
Cajanus cajan L.	*Rhizobium* + PSB	Grain yield increased from 1828 to 2660 kg/ha	Ade et al. (2018)
Vigna radiata L.	PSB + *Aspergillus awamori*	Grain yield increased from 850 to 1260 kg/ha	Venkatarao et al. (2017)
Vigna mungo L.	*Bradyrhizobium japonicum*	Grain yield increased from 736.00 to 980.00 kg/ha	Choudhary et al. (2016)
Lens culinaris L.	Rhizobium + PSB	Grain yield increased from 492 to 706.48 kg/ha	Rasool et al. (2016)
Vigna unguiculata L.	Rhizobium + PSB	Seed yield increased from 9.20 to 16.09 Quintal/ha	Meena et al. (2018)
Pisum sativum L.	RDF (Recommended Dose of Fertilizer) + PSB	Seed yield increased from 14.55 to 16.30 g per plant	Kothyari et al. (2017)
Vegetables			
Abelmoshus esculentum L.	*Pseudomonas* spp.	23.5%	Rafique et al. (2018)
	Bacillus spp.	21.0%	
Capsicum annuum L.	*Azotobacter spp.*	Fruit weight increased from 95.52 (control) to 130.30g	Ratnawati Syafruddin (2018)
Lagenaria ciceraria L.	*Azotobacter* and PSB Under integrated nutrient management	Fruit yield increased from 170.16 (control) to 380.61 Quintal/ha	Patle et al. (2018)
Solanum melongena L.	*Azotobactor* and *Azospirillum*	Fruit yield increased from 21.50 to 37.21 tons/ha	Muhammad et al. (2017)
Brassica oleracea L. *var. Capitata* L.	*Azotobactor*	Head yield increased from 26.55 to 31.77 tons/ha	Sarkar et al. (2010)
Cucumis sativus L.	*Azospirillum* and PSB Under integrated nutrient management	Fruit yield increased from 22.04 to 41.24 tons/ha	Kanaujia and Daniel (2016)
Momordica charantia L.	*Azotobacter*, PSB	Fruit yield increased from 7.02 to 41.24 tons/ha	Prasad et al. (2009)
Phaseolus vulgaris L.	*Rhizobium*	Yield increased from 143.88 to 150.63 Quintal/ha	Meena et al. (2018)
Allium sativum L.	PSB	Bulb weight increased from 22.32 to 29 g	Dutta et al. (2018)
Allium cepa L.	*Azotobacter*	Bulb fresh weight increased from 100.7 to 120.7 g	Kurrey et al. (2018)

Table1(adapted from Gautam et al., 2021).

3.1.4. Inoculation of Biofertilizers

An inert, nontoxic, organic, and cheap carrier material is mixed to biofertilizers to assist in enhancing their effectiveness (Gautam et al., 2021). Additionally, the carrier should be able to adhere to seeds and root tips, as well as carry water and bacterial cells for extended periods of time without compromising the biofertilizer's effectiveness. Vermiculite, charcoal, farmyard manure, and neutralized peat soil are the most common carriers for biofertilizer inoculation (Sundaram, 1999). Biofertilizer can be applied as a solid or a liquid form and following methodology would be used to inoculate plants.(Figure2)

Different inoculation techniques of biofertilizers

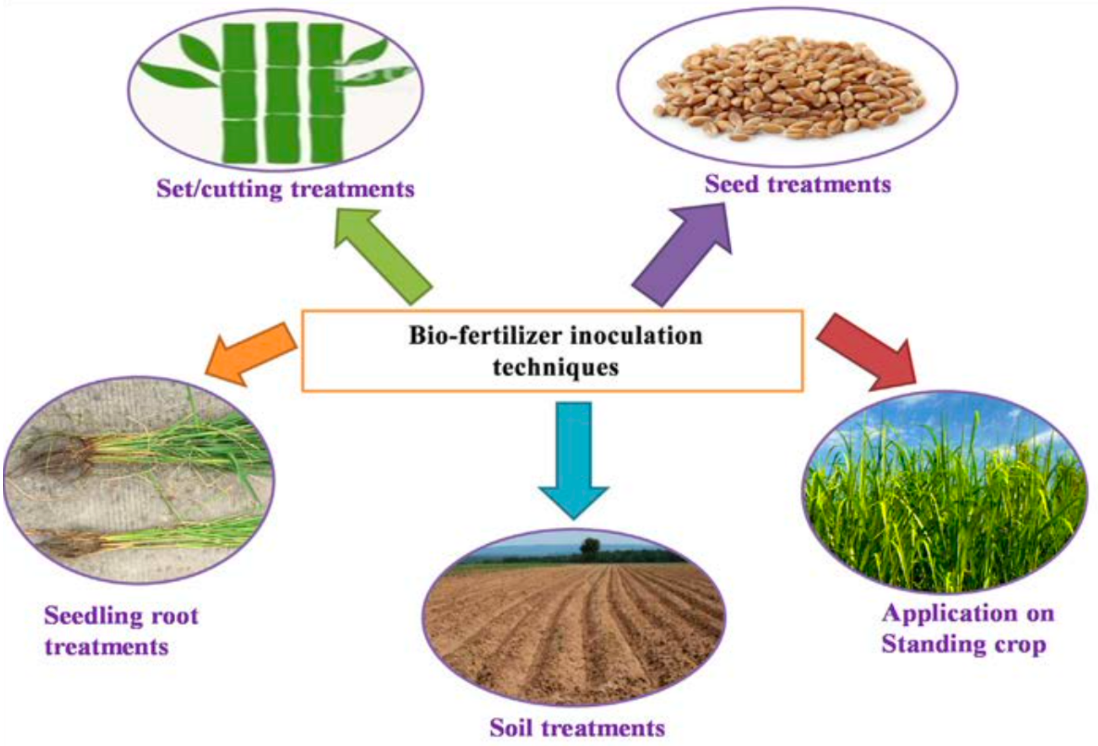

Figure2(adapted from Gautam et al., 2021).

As Figure 2 shows, the major methods of biofertilizers inoculation includes seed treatments, cutting set treatments, seedling roots treatment, soil application and application on standing crops. To be more specific, seed treatment is most commonly found in inoculating cereal crops, pulses, and oilseeds. Sugarcane, potato, and banana suckers commonly receive the cuttings/bagging treatment, they are treated with liquid biofertilizer solution prior planting. (Sundaram, 1999). Plantation crops, vegetable, flower, and agroforestry species are generally treated with seedling root treatment. The soil application method allows biofertilizers to be applied directly to the soil, and almost all crops can benefits from them (Gautam et al., 2021). Lastly, for the yearly pruned perennial crops, the method of application on standing crops could be applied (Sundaram, 1999).

3.1.5. Quantify the effects of using biofertilizers in agriculture---global meta analysis

For the purpose of assessing the performance of biofertilizers, a review of a meta-analysis that carried out by Lukas et al.(2018) entitled " Improving Crop Yield and Nutrient Use Efficiency via Biofertilization-----a Global meta-analysis". An evaluation of the literature relevant to biofertilizers was conducted by the authors in order to measure the impact of biofertilizers on crop and implementation efficiency as well as nutrient utilization efficiency. In the meta-analysis, the studies that compared biofertilizer applications to non-treated controls under the similar climate conditions were selected. Within the period between May 2015 and February 2016, peer-reviewed publications were obtained from web sources of Science (Schütz et al, 2018). It was determined that 172 of the studies analyzed in this meta-analysis were eligible for the meta-analysis, which resulted in a total of 1726 pairwise comparisons(Schütz et al, 2018).

In this meta-analysis, biofertilizers are divided into five categories: Arbuscular mycorrhizal fungi(AMF) P solubilizer, N fixer, the combined process of solubilizing P and fixing N and other biofertilizers with unspecified action mechanisms (Schütz et al, 2018). Cereals, root crops, legumes, and vegetables were the main crop categories studied and cotton, oil crops and spices such as anise and fennel were considered other crops. Microbial inoculants and their effects were structured based on their activities of solubilizing P and fixing N (Schütz et al, 2018). Furthermore, in order to quantifying the impacts of biofertilizers on crop yield, the authors compared the percent change in dry matter yields of selected crop types before and after inoculation(Schütz et al, 2018). The meta- analysis also calculated nitrogen (N) and phosphorus (P) nutrient-use efficiency before and after nutrient-inoculation to quantify the impact of biofertilizers on nutrient-use efficiency.

Several major findings were revealed in this extensive meta-analysis. Firstly, an overview of the effects of biofertilizers on the major crop categories were presented in this study as shown in Figure3. Changing yields as a percentage (A), the increase in P use efficiency (B), and the increase in N use efficiency (C) in responses to biofertilizer applications for different crops were summarized respectively(Schütz et al, 2018). A marked yield increase of 15 % to 17% was observed when biofertilizers were inoculated in all crop categories compared with the non-inoculated controls. The yield response of root crops was much lower than other crop categories, although legume crops responded much more favorably to inoculation than other crops. It was observed that legumes, cereals and vegetables had an increased efficiency in utilizing phosphorus. This study also showed an improvement in nitrogen use efficiency in legumes and cereals, however the difference was small in root crops and other crops. Biofertilizers led to an overall increase of approximately 7.5 kg yield per kg P in the phosphorus use efficiency with legumes exhibiting the most significant increase. The root crop category and other crops were found to have the least improvement. A similar increase was found in nitrogen use efficiency through biofertilization, with an increase of approximately 6 kg yield per kg N. In terms of nitrogen use efficiency, legumes demonstrated the highest level of effectiveness compared to other crop categories. A further outcome of the study was a review of the yield impact by assessing yield changes in response to different fertilizer applications (Figure4).The effect of AMF and the combination of N fixer and P solubilizer is more prominent. Using biofertilizers with both functional traits in combination has been proved to be more successful than applying biofertilizers with each trait separately.

The changes in yield and P use efficiency (PUE) and N use efficiency (NUE) after application of biofertilizer.

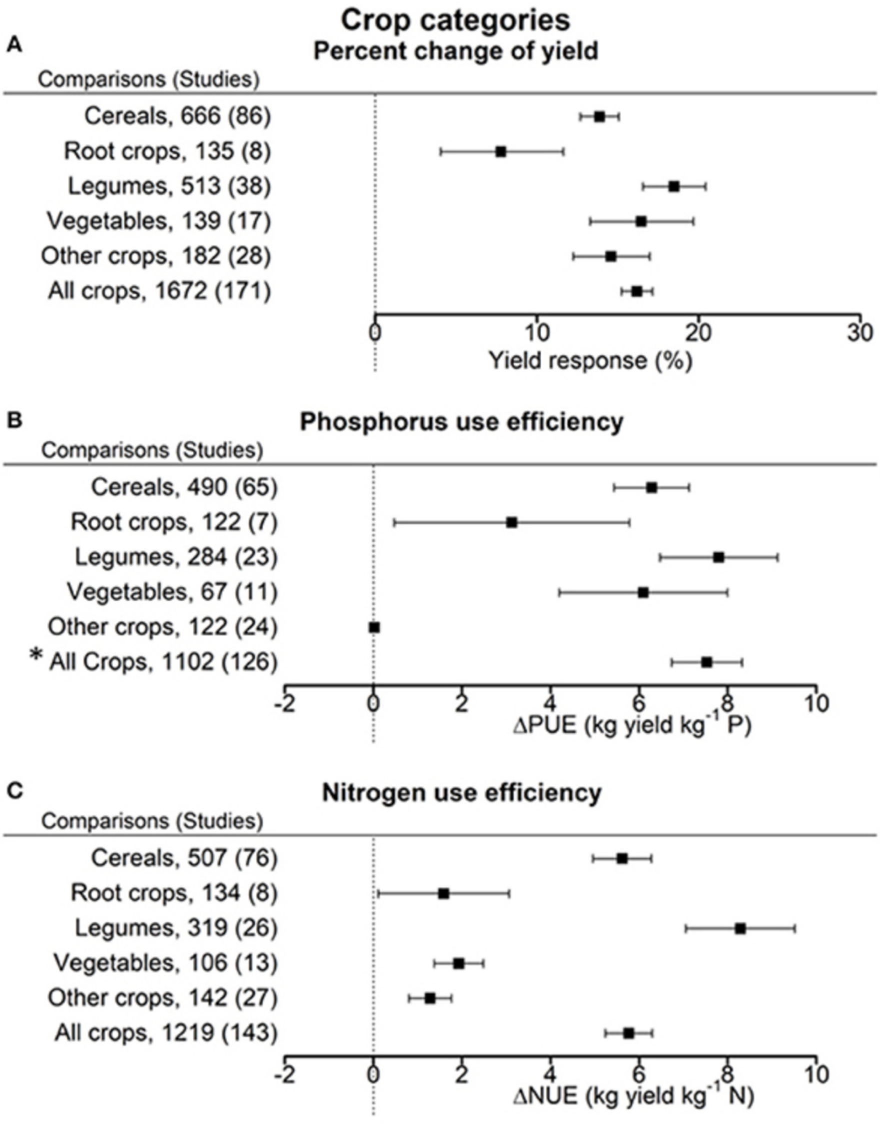

Figure3(Adapted from Schütz et al, 2018).

The percent change in yield after applying different categories of biofertilizers.

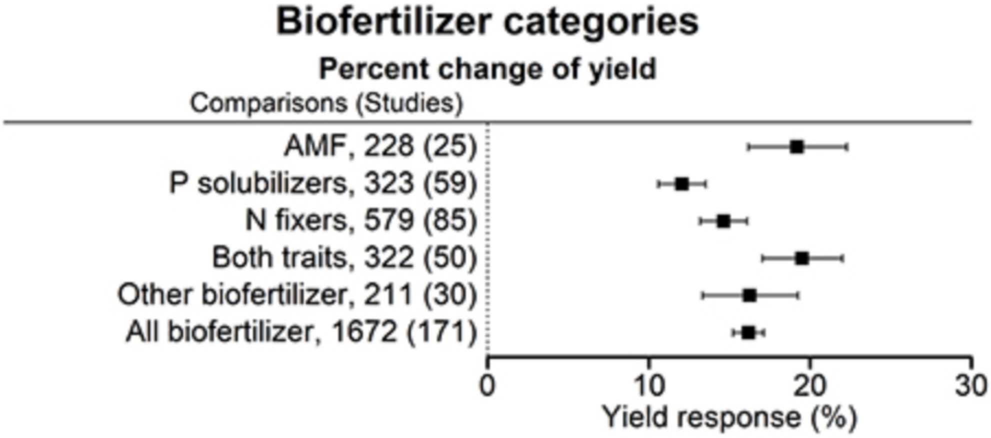

Figure 4(Adapted from Schütz et al, 2018).

3.2 Case study---- Biofertilization in Asia

A large portion of the population in Asia is dependent on agriculture. Agriculture today faces serious difficulties such as loss of soil fertility, increased pest infestations, disease outbreaks and subsequently reduced ecosystem productivity. As a result of over-reliance on chemical fertilizers, soil health and the broader ecosystem continue to be negatively affected in this region. China and Vietnam are the countries with the highest inputs of chemical fertilizers (Table2).Over the last few decades, farmers from China have applied up to 500 kg/ha of chemical fertilizer annually, and their crops currently receive approximately 70% more chemical input than those in other countries(Young et al.,2018). Similarly, over 10 million hectares of agricultural land in Vietnam receive high applications of mineral fertilizers. Between 1995 to 2000, there has been an increase of chemical fertilization in Vietnam per year, and the increase in industrial fertilizer production still falls short of market requirements (Barrett and Marsh, 2001).

Chemical fertilizers consumption in Asian countries

	Fertilizer consumption (kg ha^{-1} $year^{-1}$)	Nitrogen (N) (Tons)	Phosphate (P_2O_5) (Tons)	Potash (K_2O) (Tons)
China	503	30,462,000	15,657,000	13,726,000
Vietnam	430	1,636,759	803,111	598,960
Thailand	162	1,826,981	322,580	568,789
Myanmar	18	138,791	31,411	24,758
Cambodia	17	55,902	5867	4327
Lao PDR	n/a	n/a	n/a	n/a

Table2 (Adapted from Atieno,2020).

Agroecological practices, and more specifically beneficial microorganisms, can offer a more sustainable and affordable alternative to chemical inputs for improving soil health while sustaining crop production. The vast expanses of agricultural land in Asian countries offer great potential for the development and utilization of biofertilizers. The use of biofertilizers contributes significantly to integrated nutrient management and can result in economic benefit by decreasing the consumption of chemical fertilizers. Due to the increasing demand of biofertilizers in Asia, farmers are being encouraged to use biofertilizers in several countries (Atieno et al.,2020). Therefore, this case study provides an overview of biofertilizers to emphasize that the production and distribution is important in Asia and particularly in China.

3.2.1 Agroecological practices adoption initiations in Asia

The Asian governments are developing increasingly innovative policies to reduce chemical fertilizer use and ensure crop productivity while adapting to climate change. China, for example, established the Action Plan of Zero Growth on Chemical Fertilizers in 2015, which emphasized the demand for adapting the trend of biofertilizers application, improving the efficiency of distributing resources , and promoting sustainable management practices to reduce chemical fertilizer applications (Atieno et al.,2020). As part of its Action Plan for Zero Growth on Chemical Fertilizers, efforts were being made to reduce chemical fertilizer usage by 20% (Atieno et al.,2020) . The relevant Chinese agencies are responsible for both manufacturing and quality inspection of new microbes introduced into the Chinese market as well as for educating farmers about the use of biofertilizers through demonstrations and extension programs(Atieno et al.,2020).

The promotion of organic agriculture and 'chemical-free' crops has also been developed in Vietnam, Cambodia, and Thailand(Atieno et al.,2020) .A strategic plan has been designed and implemented by the Vietnamese government since 2000, which has been aimed at moving toward organic farming and fostering sustainability. For example, various policy frameworks related to producing, distributing, and applying these bio-inputs were enacted beginning in 2006. The Strategic Program was designed to promote organic inputs in agricultural production, including biofertilizers and biopesticides, along with numerous other policies. (Atieno et al.,2020). Similar initiatives have also been launched by the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF), which is aiming to encourage the use of biofertilizers as viable alternatives to chemical inputs. Due to the growing demand for 'chemical-free' crops on local and international markets, MAFF has taken the lead in developing research and field trials that show how biofertilizers increase crop yields and farmers' incomes through field trials (Atieno et al.,2020). Moreover, Farming movement initiatives such as the Alternative Agriculture Network (AAN) were established in Thailand since the 1980s with the help of local non-governmental organizations (NGOs) (Atieno et al.,2020). The introduction of alternative agricultural practices including the application of biofertilizers has provided economic and ecological benefits by improving soil quality, producing healthier foods, and protecting the environment.

3.2.2 Development of biofertilizers in in the Republic of China

The use of Rhizobium inoculants on leguminous plants started the research and development of microbial fertilizer in China. Rhizobium inoculants were one of the most commonly used microbial fertilizer products during the 1950s and 1960s(Ruan et al., 2020). A new era of bacterial fertilizers began in China in the 1950s when autogenous nitrogen-fixing bacteria, phosphorus bacteria, and bacterial fertilizers were introduced in China(Ruan et al., 2020). In the 1960s, a strain of Actinomycete was isolated from the alfalfa rhizosphere by the scientists from the Chinese Academy of Agricultural Sciences of Shanxi province , and this led to the widespread application of microbial fertilizer with nitrogen-fixing properties(Ruan et al., 2020).

During the 1970s and 1980s, Vesicular-Arbuscular Mycorrhiza (VAM) was first studied and used as a biofertilizer, and was found to have significant effects in increasing plant phosphorus nutritional conditions and improving water use efficiency(Ruan et al., 2020). The nitrogen-fixing bacteria and the compound bacteria that fix nitrogen have successively been applied for crop production since the mid-1980s to the mid-1990s(Ruan et al., 2020).During the past two decades, China's biofertilizer industry has developed rapidly due to technology advancements.

Currently, there are over 7,000 products registered as biofertilizers with a total production capacity of 30 million tons(Ruan et al., 2020). Thus recently a growing amount of attention is being given to biofertilizers and they have become the most important fertilizer for agricultural production in organic and natural farming with an annual application of 15 million tons.

3.2.3 Current status and characteristics of the biofertilizer industry in China

There has been an increase in biofertilizer production, the quality of biofertilizers has increased, and the impact of the technology is increasingly recognized when it comes to protecting the environment. Government policies and funds have also been implemented, as well as a set of industry standards aimed at regulating and monitoring the production of biofertilizers. The Ministry of Agriculture in China released the "Biofertilizer Standard", which sets specific technical requirements and test methods for biofertilizers(Atieno et al.,2020). This standard has a positive impact on the Chinese biofertilizer industry. It has guided and supervised the market, directly influenced scientific research, and improved the quality and safety of biofertilizers.

The biofertilizer industry has seen rapid growth in recent years due to the implementation of government policies and industrialization projects. China has become one of the world's largest producers with more than 3000 biofertilizer producing firms and a combined output of 30 million tons(Atieno et al.,2020). Agricultural production in China is increasingly influenced by biofertilizer adaption, which are applied to a variety of plants, from legumes and other vegetables to tobacco, trees, and flowers(Atieno et al.,2020).

The Chinese microbial fertilizer industry has several notable characteristics compared to the international industry: Firstly, in comparison with other countries, China offers a wide range of biofertilizer products(Young, 2007). In terms of new microbial fertilizer production, China is leading the way in combining organic nutrients with microorganisms and inorganic nutrients to create an effective combination. Moreover, biofertilizers have a wide range of applications. More than 13.3 million hectares of biofertilizers have been applied cumulatively in China which is covering a variety of crops(Young, 2007). Efforts have been made to improve fertilizer utilization rates and reduce the amount of chemical fertilizers applied, thereby decrease environmental pollution caused by excessive fertilizer use. Another notable characteristic of Chinese biofertilizer industry is the large production scale of biofertilizers, with more than 30 million tons of production capacity developed in China(Young, 2007).

3.2.4 An overview of biofertilizer use in China

The Republic of China's central and local governments support extensive applications of biofertilizers in order to promote sustainable agriculture. It has become increasingly common to use biofertilizer products for crops(Mostly applied to cereals, followed by oilseeds, vegetables and fiber crops)(Ruan et al.,2020). For the application of biofertilizers, major programs include the production of rhizobia, the production of P-solubilizing microbes for vegetable production, as well as the production of AM-inoculants for use in horticulture and in melons(Young,2007).
A number of positive results have been found in this research because biofertilizer has been widely used in a variety of plants and trees. For example, soybean yields were increased by more than ten percent by using the soybean rhizobium inoculation technology(Young,2007). The Republic of China produces soybeans for vegetable use extensively, and exported to Japan. Therefore, on the international market, maintaining superior quality is a crucial factor determining the export value of soybeans.

There was a time when farmers used excessive chemical fertilizers, which led to inferior soybeans. In the Republic of China, the Department of Soil and Environmental Sciences has been actively involved in the production and distribution of efficient inoculum, including liquid and solid biofertilizers, to help in promoting the development of high quality soybeans while increasing yields for export and consumption in other countries. Figures 5 shows the increase in the area of inoculated crops over the years. An estimated 65,091 ha of soybean farmland was inoculated with biofertilizers from 1987 to 2004((Young,2007). Rhizobia inoculants have also resulted in significantly increased economic gains for farmers during the same period(Young,2007). Additionally, as the use of chemical fertilizer was reduced, and groundwater contamination caused by nitrogen leaching was dramatically decreased.

Total Area Covered(in Hectares) Under Biofertilizer Application Over the Years in China

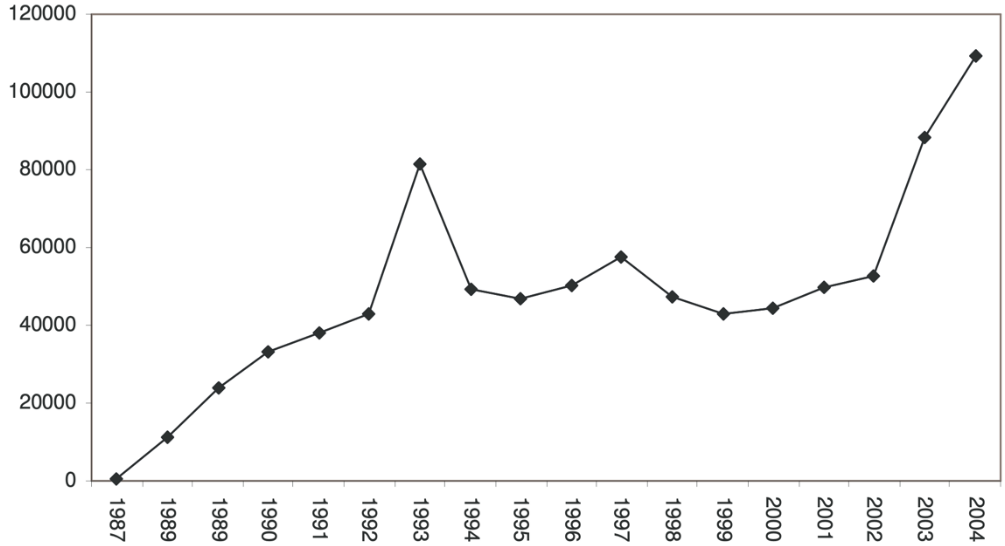

Figure5(Adapted from Young, 2007).

There has also been great success using biofertilizers on corn. In cooperation with Heilongjiang Academy of Agricultural Sciences, Century AMMS company (Beijing) has successfully applied a biofertilizer named 'woke' to corn on four different treatments. The outputs from treatments 4 (T4), 5 (T5), and 6 (T6) were 12746.32 kg/ha, 13123.64 kg/ha, and 13003.92 kg/ha(Figure6). In comparison with trials without applying biofertilizer, the yields increased by 13.49 %, 15.97 %, and 15.20% respectively(Young,2007). In addition, biofertilizer also increased soil bacteria numbers, while using high-throughput sequencing, the results demonstrated an increase in beneficial soil microbes as well.

Increased yield of corn after applying biofertilizer

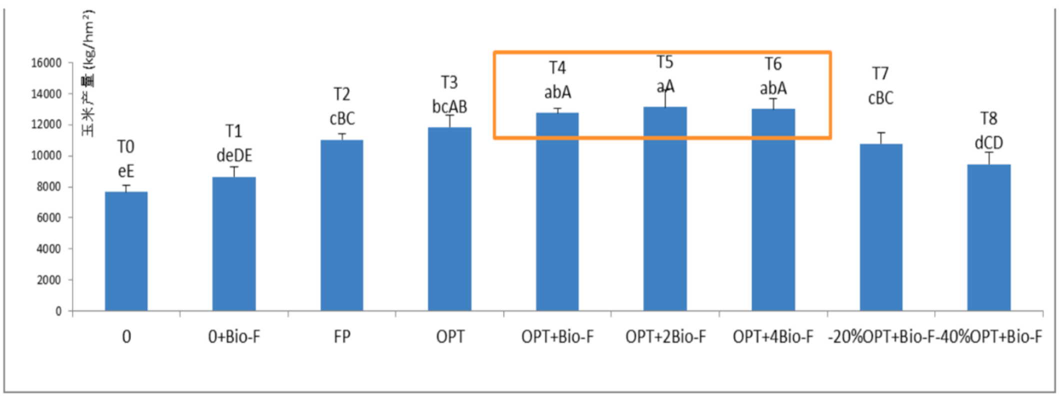

Figure6(Attained from Young,2007).

3.2.5 Observed impacts of biofertilizers on Chinese agriculture and soil health

Agronomic practices play an irreplaceable role in ensuring sustainable agricultural production capacity and green development by improving the nutrients use efficiency, ensuring soil and plant health, increasing crop productivity and reducing the amount of chemicals applied. The unique characteristics and multifaceted effects of microorganisms determine the function of biofertilizers. A brief overview of the impacts and benefits of Chinese biofertilizers on agriculture could be summarized as follows:

1. A healthy and productive soil is maintained and improved by microbial activity. The microorganisms provide benefits such as preventing soil degradation, maintaining a healthy microbial community, enhancing soil productivity, and improving soil quality.
2. Organic materials can be efficiently utilized by microorganisms in straw and other organic materials;
3.In order to improve nutrient supply and improved fertilizer utilization, microorganisms play a key role in nitrogen fixation and activation of soil nutrients; Biofertilizers can greatly reduce chemical fertilization, increase yield and make fertilization more economical.
4. The use of microorganisms is extremely valuable for overcoming obstacles like the overuse of chemical pesticides, poor plant growth, accumulation of hazardous materials and imbalances within the microbial community during continuous crop production and improving the quality of the final product.
5. It makes crops more drought resistant, flood resistant, cold resistant, and disease resistant by using microorganisms.

The core work of selecting, validating and protecting intellectual property of new functional strains is critical for to increase demand for Chinese biofertilizers, especially innovations based on the "safe, high-quality, sustainable" characteristics of green agriculture and the properties of microbial fertilizers. Considering the positive impacts that biofertilizers have on the soils of organic farms, they are becoming the preferred input for Chinese green agriculture in the future, and the success of green agriculture would not be achieved without biofertilizers.

4.0 Global industrial analysis: Current status and forecast

There has been an increase in concern about the impact of agricultural practices on the environment in recent years, agribusinesses are increasingly using natural sources of nutrition instead of chemical sources. (Joshi and Gauraha,2022). Farmers are increasingly adopting sustainable agricultural management practices, including the application of biofertilizers, which is pushing the global biofertilizer market to grow rapidly.

When looking at the global market for biofertilizers by geography, and in particular by continent, it can be said that biofertilizers are most commonly used in North America, while Europe follows closely behind in second place, followed by Asian countries third. South America occupies the fourth position and other countries at the end (Figure 7)(Sansinenea,2021). The increasing adoption and application of biofertilizers in sustainable agriculture has been driven due to their wide range of benefits. In North America, the United States is the largest market for biofertilizers due to the high price of mineral fertilizers and the negative effects they have on soil and ecosystem (Sansinenea,2021). Additionally, fermentation technology has grown in North America, which also contributes to the production and application of biofertilizers in the United States(Sansinenea,2021). Canada and Mexico are still developing markets in the North American Biofertilizer taxonomy. However, bio-based products are experiencing a surge in demand because of a positive outlook in the agriculture sector. A growing use of biobased nutrition products and higher food standards are expected to sustain the North American market in the foreseeable future.

Global Biofertilizer Market Share (%) by Geography

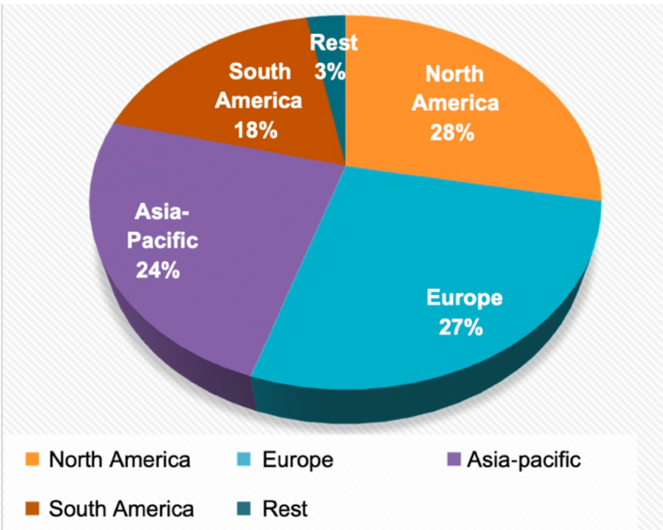

Figure 7(Obtained from Sansinenea,2021).

Soils in South Asia are severely deficient in P and K, biofertilizers can therefore be useful to prevent future nutrient deficiency problems for agriculture in this region and would likely be the most promising product for the market. As a result, growers in regions such as Asia, and especially in India, are gradually acknowledging the benefits of biofertilizers. They are not only being applied to fruit and vegetable products, but also being used in traditional crops such as soybeans and sugarcane. An emerging market like India is estimated to have a total agrochemical market worth more than 16000 crores which indicates a large opportunity for biofertilizer market in the future.

There are several factors that contribute to the worldwide adoption of biofertilizers. First of all, organic farming is becoming increasingly popular. Growing amount of consumers and increasing incomes have led to an increase in demand for organic products, which provides people with the opportunity to consume more organic food(Joshi and Gauraha,2022). Therefore, the need for biofertilizers has increased in developed countries such as Europe and North America due to the increasing demand in organic food and the increasing awareness among the public of the food safety issues. In addition, the biofertilizer market has also benefited from the expanding area of organic farming, the increasing availability of natural foods, its optimal economic value, and the increasing acceptance of innovative technologies(Joshi and Gauraha,2022). Moreover, there is a growing concerns about synthetic agrochemicals' potential adverse effects on the environment, including food chain contamination and soil degradation, which has further increased the use of biobased products. The common agricultural policy also promotes sustainable agriculture by limiting chemical fertilizers application and promoting the adoption of biofertilizers(Joshi and Gauraha,2022).

Economically, biofertilizers are more profitable for farmers because they create better break-even margins, higher nutrient utilization efficiency, and they contribute to reduce chemical fertilizer utilization. (Mishra and Dash, 2014). In selected countries such as Egypt, Colombia, Pakistan and Thailand, it is evidenced that biofertilizers are more profitable and have reduced the consumption of chemical fertilizers significantly among the crops that are being tested (Joshi and Gauraha,2022). Since biofertilizers are cheaper than chemical fertilizers, there is an opportunity for greater economic return with their implementation. Policymakers may find this to be quite valuable as it will help them gain a better understanding of farmers' decision to incorporate biofertilizers in their fields.

5.0. Challenges of biofertilizers

Biofertilizers have been demonstrated to have great potential to maintain a sustainable environment and decrease chemical fertilizer input. In addition to enhancing the biodiversity of microorganisms in soil and increasing its fertility, Plant diseases can also be managed with biofertilizers under stressful environments. However, there are some limitations that prevent biofertilizers from being widely accepted and commercialized at the global scale. Due to these limitations, investors have doubts about the applications of the biofertilizers and the restrictions could affect the production and marketing of biofertilizers.

5.1 Shelf- life constraints

The survival of microorganisms depend on the process of formulation during product preparation, storage, and application (Bharti and Suryavanshi,2021). These factors determine the value of commercial biofertilizers and their potential success. Biofertilizers based on solid carriers generally have a shelf life of six months, while liquid formulations remain effective for up to two years (Bharti and Suryavanshi,2021). Solid carriers used in biofertilizers are susceptible to contamination because they do not contain a properly sterilized carrier material. Additionally, the amount of water in the carriers decreases over time, making them difficult to remain viable. Moreover, they are lacking the ability to resist high temperatures and UV radiation(Bharti and Suryavanshi,2021). Conversely, the development of liquid biofertilizers was designed as an alternative to biofertilizers. The inoculum concentration was higher, therefore they exhibited a tolerance for high temperatures and UV radiation(Bharti and Suryavanshi,2021). Compared to solid bioformulations, liquid biofertilizers can be stored for up to two years, however, it is less favorable because of its high production costs(Bharti and Suryavanshi,2021).

5.2 Environmental constrains under natural conditions

Based on the laboratory test results, microbial inoculants are prepared as pure cultures. However, in the field, there are several other factors that need to be taken into consideration, such as biodiversity of microbes, genetics, weather conditions, amount of available water and the application of pesticides or herbicides. Laboratory simulations cannot simulate such natural constraints since these factors are unpredictable. Unlike colonies on a petri plates, bacteria in natural conditions usually exist as biofilms(Kumawat et al ,2021). Therefore, the researchers suggested developing mathematical models that would allow them to better understand how plants and microbes interact under natural conditions.

5.3 Sales and marketing restrictions

A lack of marketing channels and infrastructure prevents these biofertilizers from being more widely available. Marketing biofertilizers is challenging since they contain microbes with limited shelf lives (Barman et al., 2017). Due to different weather conditions, distribution, storage, and transportation of the material to farmers are also difficult. Furthermore, the packaging, labeling, and pricing of these biofertilizers are not governed by any regulations and standard operating procedures (Barman et al., 2017). The government offers subsidies for biofertilizers sales in different countries. However, the system is inconsistent and disorganized across countries, causing wide differences in cost within the industry. Moreover, the products' end users such as farmers in agriculturally-dependent countries are generally poor educated. There is a lack of awareness of biofertilizers and limited information about microbe-dependent agricultural techniques among the general public, making outreach difficult to biofertilizers.

5.4 Farmer acceptance

There are many potential benefits to using biofertilizers, such as enhancing grain yields, decreasing production costs and improving soil fertility.Even though bio-inoculants have a wide variety of metabolic potential, there is still a lack of acceptance among consumers and a variety of factors limiting their application by farmers. Therefore, the key to ensuring the wider acceptance of bio-inoculants is by addressing the limitations, issues, and challenges that consumers face while using bio-fertilizers.

Because of the low prices, biofertilizers are inexpensive for consumers and their ability to enhance soil health, improve soil texture, and increase water holding capacity makes them more beneficial for agriculture (Kumawat et al ,2021). However, the potential of biofertilizers in increasing grain yields sustainability is not well recognized by rural farmers. There is a problem with the lack of information and resources on how they can develop the appropriate amount, the optimal application time and the correct method of applying bio-fertilizers as well as the benefits of agrochemical replacements compared to biofertilizers(Kumawat et al ,2021). Apart from these main limitations, there are also some other limitations that can prevent wide-scale market adoption including lack of financial support and subsidies from government; technical challenges such as inadequate infrastructures and lacking guidance from technical expertise; other limitations that could limit their wider application such as lack of confidence or interests in the adoption of biofertilizers.

Additionally, entrepreneurs lack the skills and knowledge to properly apply biofertilizers, as well as limited access to resources to support significant marketing initiatives. Agrochemical industries need to work collaboratively with policymakers to popularize biofertilizer technology in order to regain a competitive position against traditional biofertilizers (Kumawat et al ,2021). Promotion policies are implemented by governments for the purpose of educating farmers and demonstrating the effectiveness of a variety of alternative approaches. In order to improve the acceptance of a product and to create demand at the same time, active consumer participation in innovative research projects is necessary. Moreover, both central and regional governments should support widespread acceptance and adoption of biofertilizers to encourage sustainable agriculture. There are various approaches to improving the grain yield and the health of crops in this context such as the production of biofertilizers, extension programs to provide consumers with knowledge on how to use such inoculants or a demonstration program to inform farmers the economic advantage of applying biofertilizers on crops versus untreated crops.

6.0. Conclusion

As a result of the pressing need for sustainable agricultural goal achievement, diminishing dependency upon agrochemicals, and a growing preference of consumers for more nutritional foods, there is now more opportunity for the production and application of biofertilizer products in agriculture as an alternative approach. Considering the growing population worldwide, there is an increasing need for of a sustainable agricultural system that can effectively supply the food and other needs of the population. Increasing crop production requires higher energy input in today's rigorous cropping systems. Fertilizers are used to enhance crop yield, however, they are potentially harmful if they are used for a prolonged period as they can cause soil degradation and several negative impacts on the environment. In order to meet food demand and conserve the environment at the same time, a sustainable agricultural production approach that is eco-friendly is needed. The use of biofertilizers can be considered as one of the alternative solutions to resolve this problem in agriculture industry efficiently as they contribute to the nutritional content of the crops while maintaining the ecological balance at the same time.

Additionally, the development and supply of biofertilizers in developing countries has been a major achievement for biotechnology companies. Farmers, businesses and other sectors can benefit from biofertilizers that solve the challenges currently faced by agriculture industries. However, the usage of biofertilizers is related to knowledge of the production process, application approaches and the promotion of biofertilizers are crucial for ensuring proper application. Therefore, further research is necessary for this technique to improve the efficiency of this technique.

7.0. Recommendations

- In the presence of stressful conditions, the investigation of the microbial persistence of biofertilizers should be highlighted.
- Stringent guidelines and regulations must be enforced throughout every stages in the process, from the production, distribution to the application in the field;
- Promoting and integrating the use of biofertilizers with other agroecological practices so that sustainable agriculture is achieved in a variety of cropping systems;
- Building the capacity of researching and teaching institutions, government agencies, farmers, and private sectors for the dissemination of microbial technology.

Alternative agroecological practices can be developed, established, and promoted due to the growing demand for organic produce. Nevertheless, a strong and effective partnership with private sectors is also expected in order to test and adopt high-quality products. It is suggested that academic institutions, research institutions both private and governmental establish mechanisms, both locally and globally to coordinate and collaborate and demonstrate the benefits and challenges offered by biofertilizers to provide for healthy soil, healthy food and healthy ecosystems in the quest for global sustainability.

7.0. Acknowledgments

With all humility and gratitude, I would like to acknowledge my deepest thanks to all those who have helped me to put these ideas into something concrete and elevate them above the level of simplicity. This project would not have been possible without their valuable guidance and feedback.

I would like to express my deepest appreciation to my supervisor Les Lavkulich who has given me the opportunity to do such an interesting and worthwhile project on the topic of Biofertilizers for Sustainable Agriculture. He has been supporting and guiding me in completing this project from time to time, which has also helped me in conducting a lot of research and has led me to learn about so many new things. In addition, I wish to take this opportunity to extend my sincere appreciation to Julie Wilson, our Academic Coordinator, for all her effort in providing me with all the assistance I needed to plan this project.

I would like to thank my collogues and friends in MLWS program who helped me a lot in gathering different perspectives and providing me different ideas in making this project unique. The support and guidance of my colleagues and friends is essential to the successful completion of any attempt.

References:

Atieno, M., Herrmann, L., Nguyen, H. T., Phan, H. T., Nguyen, N. K., Srean, P., ... & Lesueur, D. (2020). Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. Journal of environmental management, 275, 111300.

Aktar W, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol 2(1):1–12

Arun KS (2007) Bio-fertilizers for sustainable agriculture. In A.K.S., Bio- fertilizers for sustainable agriculture Jodhpur, India: Agribios pub- lishers 196–197

Acton, D. F., & Gregorich, L. J. (1995). The health of our soils: toward sustainable agriculture in Canada.

Bane, G. (1991). It's worth paying more: The benefits of alternative agriculture. Journal of pesticide reform: a publication of the Northwest Coalition for Alternatives to Pesticides (USA).

Barman, M., Paul, S., Choudhury, A.G., Roy, P., Sen, J., 2017. Biofertilizer as prospective input for sustainable agriculture in India. Int. J. Curr. Microbiol. App. Sci. 6, 1177–1186. https://doi.org/10.20546/ijcmas.2017.611.141.

Bharti, N., & Suryavanshi, M. (2021). Quality control and regulations of biofertilizers: Current scenario and future prospects. In Biofertilizers (pp. 133-141). Woodhead Publishing.

Doran, J. W., & Safley, M. (1997). Defining and Assessing Soil Health and Sustainabl e Productivity. Biological Indicators of Soil Health. CAB International, New York.

Economics of Land Degradation Initiative: Report for policy and decision makers_ Reaping economic and environmental benefits from sustainable land management(2015). Bonn, Germany: ELD Initiative and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Faeth, P., R Repetto, K. Kroll, Q. Dai, C. Helmers. 1991. Paying the farm bill: US. agricultural policy and the transition to sustainable agriculture. Washington, D.C.: World Resources Institute.

FAO. (2014). The water-energy-food nexus: A new approach in support of food security and sustainable agriculture. Food and Agriculture Organization (FAO) of the United Nation.

Fasusi, O. A., Cruz, C., & Babalola, O. O. (2021). Agricultural sustainability: microbial biofertilizers in rhizosphere management. Agriculture, 11(2), 163.

Gautam, K., Sirohi, C., Singh, N. R., Thakur, Y., Jatav, S. S., Rana, K., ... & Parihar, M. (2021). Microbial biofertilizer: Types, applications, and current challenges for sustainable agricultural production. In Biofertilizers (pp. 3-19). Woodhead Publishing.

Joshi, S. K., & Gauraha, A. K. (2022). Global biofertilizer market: Emerging trends and opportunities. Trends of Applied Microbiology for Sustainable Economy, 689-697.

Kremsa, V. Š. (2021). Sustainable management of agricultural resources (agricultural crops and animals). In Sustainable Resource Management (pp. 99-145). Elsevier.

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. Environment international, 132, 105078.

Kumawat, K. C., Nagpal, S., & Sharma, P. (2021). Present scenario of bio-fertilizer production and marketing around the globe. In Biofertilizers (pp. 389-413). Woodhead Publishing.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The concept and future prospects of soil health. Nature reviews. Earth & environment, 1(10), 544–553. https://doi.org/10.1038/s43017-020-0080-8

Magdoff, F. (2001). Concept, components, and strategies of soil health in agroecosystems. Journal of nematology, 33(4), 169.

M Tahat, M., M Alananbeh, K., A Othman, Y., & I Leskovar, D. (2020). Soil health and sustainable agriculture. Sustainability, 12(12), 4859.

Mahanty, T., Bhattacharjee, S., Goswami, M., Bhattacharyya, P., Das, B., Ghosh, A., & Tribedi, P. (2017). Biofertilizers: a potential approach for sustainable agriculture development. Environmental Science and Pollution Research, 24(4), 3315-3335.

Pretty J, Bharucha ZP (2015) Integrated pest management for sustainable intensification of agriculture in Asia and Africa. Insects 6(1):152– 182

Ruan,Z.,Ma,Q.,and Sternfeld,E.(2020).Study: Biofertilizers in China: A Potential Strategy for China’s Sustainable Agriculture:Current Status and Further Perspectives. Sino-German Agricultural Centre

Saha, B.; Saha, S.; Das, A.; Bhattacharyya, P.K.; Basak, N.; Sinha, A.K.; Poddar, P. Biological nitrogen fixation for sustainable agriculture. In Agriculturally Important Microbes for Sustainable Agriculture; Springer: Berlin/Heidelberg, Germany, 2017; pp.81–128.

Stewart, W. M., Dibb, D. W., Johnston, A. E., & Smyth, T. J. (2005). The contribution of commercial fertilizer nutrients to food production. Agronomy journal, 97(1), 1-6.

Schnitzer, S.A.; Klironomos, J.N.; HilleRisLambers, J.; Kinkel, L.L.; Reich, P.B.; Xiao, K.; Rillig, M.C.; Sikes, B.A.;Callaway, R.M.; Mangan, S.A.; et al. Soil microbes drive the classic plant diversity-productivity pattern.

Sundaram, R.N.S., 1999. Use of Biofertilizer. Extension Folder No. 17. Krishi Viigyan Kendra, ICAR-Research Complex, Goa, pp. 1–4.

Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mäder, P., & Mathimaran, N. (2018). Improving crop yield and nutrient use efficiency via biofertilization—a global meta-analysis. Frontiers in Plant Science, 2204.

Sansinenea, E. (2021). Application of biofertilizers: Current worldwide status. In Biofertilizers (pp. 183-190). Woodhead Publishing.

U.S. Environmental Protection Agency. 2Z 1987. National water quality inventory 1986 report to Congress. Washington, D.C.: Office of Water. Cited in Weinberg, AC. Low input agriculture reduces nonpoint source pollution. Journal of Soil and Water Conservation 45(1):48~50.

Vasu, D., Tiwary, P., Chandran, P., & Singh, S. K. (2020). Soil quality for sustainable agriculture. In Nutrient dynamics for sustainable crop production (pp. 41-66). Springer, Singapore.

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. Plant and Soil, 255(2), 571-586.

Wagg, C.; Jansa, J.; Schmid, B.; van der Heijden, M.G.A. Belowground biodiversity effects of plant symbionts support aboveground productivity. Ecol. Lett. 2011, 14, 1001–1009.

Young, C. C. (2007).Development and application of biofertilizers in the public of China. Business potential.

Zakeel, M.C.M., Safeena, M.I.S., 2019. Biofilmed biofertilizer for sustainable agriculture. In: Plant Health Under Biotic Stress. Springer, Singapore, pp. 65–82

Communication feature: