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# Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region

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# Abstract

A growing concern on the deleterious effects of chemical inputs to the environment has been on the rise from the excessive use of chemical inputs leading to soil and water pollution, destruction to fauna and microbial communities, reduced soil fertility and increased crop disease susceptibility. In the Great Mekong Region (GMR), a large majority of the population relies on agriculture and faces severe challenges including decline in soil fertility, increased pests and diseases, leading to lower ecosystem productivity. In this region, over-dependence on chemical fertilizers also continue to impact negatively on soil health and the wider ecosystem. Agroecological practices and beneficial microorganisms in particular, offer an affordable and sustainable alternative to mineral inputs for improved plant nutrition and soil health for optimal crop performance and sustainable production. Biofertilizers are a key component in integrated nutrient management as well as for increased economic benefits from reduced expenditure on chemical fertilizers, holistically leading to sustainable agriculture. To cope with the need for biofertilizer adoption for sustainable agricultural production, the countries in the GMR are putting effort in promoting development and use of biofertilizers and making them available to farmers at affordable costs. Despite these efforts, farmers continue to use chemical fertilizers at high rates with the hope of increased yields instead of taking advantage of microbial products capable of providing plant nutrients while restoring or improving soil health. This study explored the current agricultural practices in the six countries in the GMR (China, Vietnam, Myanmar, Thailand, Cambodia and Lao PDR), the critical need for sustainable agroecological practices with a special emphasis on biofertilizers. We highlighted the current status, distribution, adoption and gaps of biofertilizer production in the GMR, in order to obtain an insight on the nature of biofertilizers, efficacy and production standards, adoption or lack of biofertilizers in the GMR.

Key words: Biofertilizers, Great Mekong Region, Agroecological practices, Soil health

## 1. Introduction

Globally, biofertilizer development and use has been on the rise due to the universal problem of environmental degradation from an overuse of chemical fertilizers. Bio-fertilizers, defined as products containing beneficial microorganisms with the potential to improve soil fertility and crop productivity, are valuable to the environment as they reduce dependency on chemical fertilizers. This has seen an increase in efforts of formulating and promoting the adoption of these products for crop nutrition, improved soil health and sustainable agriculture. However, a high proportion of biofertilizers in the market have not been subjected to scientific scrutiny resulting to poor quality products with little or no impact on soil fertility and crop yields. The farmers lose confidence in these products and end up reverting to the traditional practice of applying chemical fertilizers, instead of taking advantage of beneficial microorganisms capable of nourishing their soils.

There is immense potential in developing and utilizing biofertilizers in Asia especially in the large expanse of agricultural land in the Great Mekong Region (GMR). The aim of this study was to review the current status, distribution, adoption and gaps of biofertilizer production in the GMR (China, Vietnam, Myanmar, Thailand, Cambodia and Lao People's Democratic Republic). The study took a deep dive into reviewing literature on biofertilizers in the GMR to understand the level, or lack thereof, of adoption of this technology. Quality and market assessment were also done by engaging with different institutions and the private sector. The authors sought to understand and inform strategic opportunities and the enabling environment to promote development and use of biofertilizers in the GMR.

## 2. Agriculture in the Great Mekong Region

The Great Mekong Region (GMR) is an economic area of six countries connected by the Mekong River, covering an area of about 11.3 million km$^2$ and a combined population of 3.3 billion people (ADB, 2012). The countries that make up the GMR include the People's Republic of Cambodia, China, Lao People's Democratic Republic (Lao PDR), Myanmar, Thailand and Vietnam (Fig. 1). While increasingly being industrialized, the GMR predominantly engages in agriculture. Agricultural area exceeds 5.8 million km$^2$, involving 75% of the population, mostly in the rural areas (ADB, 2018; Ingalls et al., 2018; OECD/FAO, 2017; World Bank - World Development Indicators, 2019).

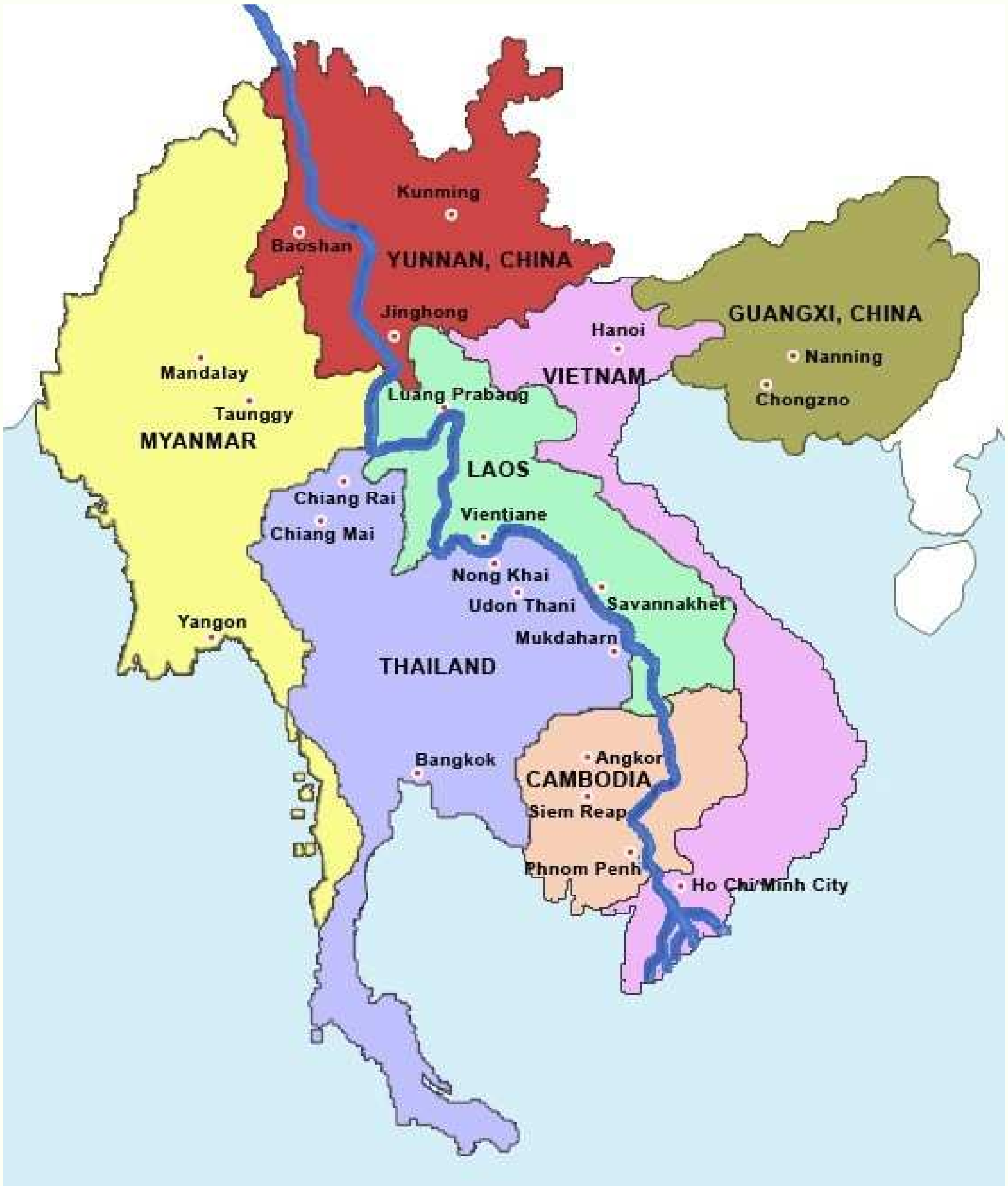

**Fig 1**. Greater Mekong Region showing Mekong River and its basin in 6 countries – China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam. Adapted from Mekong Tourism Coordinating Office (MTCO, 2020).

Rice is undoubtedly the main crop in the whole region with a production ranging from 4 to 214 million tons, from a harvested area of 1 to 31 million ha (ADB, 2018). The GMR countries provide more than 40% of the world production of rice, with Thailand reported as the number one rice exporter in 2016 (OECD/FAO, 2017). Sugar cane is one of the most cultivated crops in the region after rice, with a production of > 100 million tons in Thailand and China. Similarly, cassava production covers 2.7 million ha across the region with a total production of approximately 60 million tons (20% of the world production) (OECD/FAO, 2017). Varieties of other crops are of value in specific countries in the region. For instance, maize and wheat are top crops grown in China (260 million and 134 million tons, respectively) but their production in the rest of the region is significantly lower. Oil palm and rubber trees are very important in Thailand, with a production of about 15 million tons per year (OECD/FAO, 2017). Vietnam has become a leading exporter of coffee, pepper, and rubber while Cambodia is currently putting more emphasis on other profitable crops such as legumes and vegetables (ADB, 2018). In Myanmar, top crops include pulse and oilseed legumes as well as other non-legume oilseeds (FAOSTAT, 2019; MOALI, 2016).

Legume crops have played a major role as part of sustainable cropping systems throughout the six countries of the GMR, though mainly in Myanmar as they represent 44% of total cropped area as compared to just 5–10% in China, Lao PDR and Thailand. Wide ranges of species are cultivated in the GMR, including but not limited to beans, peas, groundnuts, pigeon peas and lentils. Groundnut, soybean and dry beans are the most common legume crops grown in all the six countries (Table 1; FAOSTAT, 2019). Mung bean (also called green gram) is a common crop grown in Asia that accounts for about 90% of the total global production. Although India is the largest producer with more than 50% of world production, mung bean represents approximately 19% of legumes produced in China, and is receiving increasing attention in Cambodia, Thailand and Myanmar (Goletti & Sovith, 2016).

**Table 1**: Main legume crops grown in the GMR (2017 data).

| | **Groundnut** | | **Soybean** | | **Dry beans** | |
|---|---|---|---|---|---|---|
| | **Area harvested (ha)** | **Production (tons)** | **Area harvested (ha)** | **Production (tons)** | **Area harvested (ha)** | **Production (tons)** |
| China | 4,608,000 | 17,092,000 | 7,341,972 | 13,149,485 | 801,588 | 1,322,214 |
| Myanmar | 1,033,942 | 1,582,693 | 139,736 | 209,470 | 3,182,144 | 5,466,166 |
| Vietnam | 195,352 | 459,849 | 67,993 | 101,856 | 149,702 | 162,832 |
| Cambodia | 18,000 | 20,000 | 104,000 | 168,000 | 66,871 | 83,167 |
| Thailand | 30,000 | 32,000 | 31,000 | 54,000 | 93,004 | 71,076 |
| Lao PDR | 18,887 | 49,105 | 4,260 | 7,960 | 2,520 | 4,475 |

Source: FAOSTAT, 2019

## 1.1 Conventional agriculture and fertilizer use

In the GMR countries, increasing population pressure and demand for agricultural land has led to agricultural systems dominated by conventional and intensive practices that include conventional tillage, mono-cropping and overuse of mineral fertilizers (Mathew et al., 2012; Mertz et al., 2009; Ziegler et al., 2011). Cropping systems influence biological, physical and chemical soil properties with significant impacts on crop productivity and sustainability of the ecosystem (Mathew et al., 2012). In the GMR, such conventional practices have led to the degradation of the ecosystem with detrimental effects on soil fertility, climate change, crop production and crop health (Alori & Fawole, 2017; Fox et al., 2014). In order to ensure adequate food supply and self-sufficiency of the growing population, farming systems in the GMR inevitably require the addition of increasing rates of mineral fertilizers to meet the nutrient needs for crop growth and yield. This instead leads to significant negative environmental impacts such as poor/infertile soils, air and groundwater pollution from leaching, greenhouse gas (GHG) emission and decrease of biodiversity (Zhen et al., 2006).

China and Vietnam have recorded the highest levels of chemical fertilizer inputs in the region (Table 2). Chinese farmers have applied up to 600 kg $ha^{-1}$ per year of mineral fertilizers over the last couple of decades (Yang et al., 2018), and currently apply approximately 70% more chemical inputs to their crops as compared to the rest of the world (Times, 2017). Vietnam is also in a similar situation where the demand and use of fertilizers is very high for over 10 million ha of agricultural land. From 1995 to 2000, the amount of fertilizers used per year increased by 7% (N), 8% (P) and 10% (K), and continuously increasing industrial production of fertilizers is still insufficient to meet the market demand (Barrett & Marsh, 2001). Vietnamese farmers prefer to use chemical N fertilizers for their legume crops at rates of 30 to 150 kg N $ha^{-1}$ over use of legume inoculants as they are readily available thus leading to significant increases in production costs (>$100 million $year^{-1}$) (Herridge et al., 2008). On the contrary, Myanmar, Cambodia and Lao PDR have reported low levels of N, P and K fertilizers application over time (Table 2), mainly attributed to high fertilizer costs not affordable to most smallholder farmers (FAOSTAT, 2019).

**Table 2**. Mineral fertilizer consumption in the GMR (2016).

| | **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 | 5,867 | 4327 |
| Lao PDR | n/a | n/a | n/a | n/a |

Source: FAOSTAT, 2019; World Bank, 2019

## 1.2 Importance of restoring soil health and soil fertility for stopping soil degradation

Soil health is defined as the capacity of the soil to function as a living system, with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. It is based on the interaction, balance and stability of the physical, chemical, and biological properties of soil, which has direct effects on nutrient cycling, soil structure, water availability and pests and diseases, ultimately affecting crop health and yield (FAO, 2008; Patil & Solanki, 2016).

In the GMR, soil degradation has become a major constraint due to erosion, depletion of nutrients and soil organic carbon (SOC), aggravation of soil salinity and acidification, decline in biodiversity of natural, agricultural, and forest ecosystems (Lal, 2015; Pimentel & Burgess, 2013). Extensive use of heavy doses of mineral fertilizers (such as synthetic ammonia, urea, ammonium phosphate or triple superphosphate) in industrialized agricultural systems have further affected soil health through leaching, eutrophication, GHG emission and environmental pollution (Lal, 2015). Moreover, soil degradation has strong negative economic impacts since a large part of the population relies on agriculture as a primary source of income (Lal, 2016). To date, more than 500 million hectares of tropical arable land and 33% of earth's land surface globally face decline in soil health (Lal, 2015; Lamb et al., 2005). Restoring the soil fertility of degraded agricultural soils is one of the most-pressing topics that holds the key to dealing with three main challenges i.e. feeding the growing population, mitigation of climate change and biodiversity conservation, while achieving a productive and sustainable system.

In the GMR, governmental initiatives are increasingly being developed to reduce the use of chemical fertilizers while ensuring high crop yields and resilience to climate change. For instance, in 2015, the Ministry of Agriculture in China published the *Action Plan of Zero Growth on Chemical Fertilizers by 2020* which emphasizes the need of China to adjust the fertilizers application structure, increase in application efficiency and promote alternative practices to drastically reduce the use of mineral fertilizers in agricultural systems (Chan, 2015). Several initiatives have also been started in Vietnam, Thailand and Cambodia to promote organic farming and ‘chemical-free’ crop production. Implementation of such agroecological practices may improve soil health by reducing reliance on external inputs and convert low-input systems into productive lands.

## 3. Agroecology: A focus on biofertilizers

The term agroecology is loosely defined to integrate several aspects of achieving an environmentally-friendly and socially-sensitive approaches to agriculture, focusing on production as well as on the ecological sustainability of the production system (Altieri, 2018). The Association of Agroecology Europe outlined a holistic definition of agroecology as follows: *“Agroecology is considered jointly as a science, a practice and a social movement. It encompasses the whole food system from the soil to the organization of human societies. As a science, it gives priority to action research, holistic and participatory approaches, and trans-disciplinarity including different knowledge systems. As a practice, it is based on sustainable use of local renewable resources, local farmers’ knowledge and priorities, wise use of biodiversity to provide ecosystem services and resilience, and solutions that provide multiple benefits (environmental, economic, social) from local to global. As a movement, it defends smallholders and family farming, farmers and rural communities, food sovereignty, local and short marketing chains, diversity of indigenous seeds and breeds, healthy and quality food.”* Agroecological practices have been popularized to contribute to sustainable ecosystems as they are linked to various ecological processes such as biological nitrogen fixation (BNF), nutrient cycling, carbon sequestration, soil health, and conservation of water and biodiversity (Wezel et al., 2014). They range from high technology-based practices to ecology-based practices, including no or reduced tillage, cover crops, green manure, intercropping, crop rotations, agroforestry, resource and biodiversity conservation practices, precision farming, genetic engineering and biofertilizer use (Altieri, 2018; Wezel et al., 2014).

In the face of climate change and growing demand for high crop yields, safe food and agricultural sustainability, one of the main technologies in agroecology – biofertilizers – has emerged as priority area in the GMR (Mazid & Khan, 2015). Over the past two decades, there has been different propositions of the definition of biofertilizer. However, the definition proposed by Vessey (2003) has been the most popular. A biofertilizer is thus defined 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"*. Another proposition by Fuentes-Ramirez & Caballero-Mellado (2005) later defined biofertilizer as *"a product that contains living microorganisms, which exert direct or indirect beneficial effects on plant growth and crop yield through different mechanisms"*. Biofertilizers can also be referred to as microbial inoculants, to describe preparations containing live or latent cells of an efficient microbial strain (bacteria, fungi, or algae) capable of nitrogen (N)-fixation, phosphate (P)-solubilization, or any other beneficial activity such as hormone or metabolite production (Young, 2007).

Biofertilizers are low-cost, environmentally-friendly and effective inputs with high agricultural benefits, which need to be more popularized within the farming community of the GMR (Nath & Das, 2018). They have the potential to reduce the negative impacts from chemical fertilizer use by playing a significant role in restoring soil fertility and improving crop health and yields (Patil & Solanki, 2016; Malusá & Vassilev, 2014). Inoculation with biofertilizers can also be used together with other agroecological practices for maximum benefits and can be included in intercropping and crop rotation systems, under different tillage systems and organic amendment practices (Sahoo et al., 2013).

In recent times, the central and local government agencies in the GMR countries have started to advocate for the use of biofertilizers in order to reduce application of chemical inputs and promote sustainable agriculture. In the frame of its *Action Plan of Zero Growth on Chemical Fertilizers by 2020*, China aims to reduce use of chemical fertilizers by at least 20% by 2020. Consequently, the relevant agencies in China are in charge of the production and quality control of new microbial products as well as creating awareness of biofertilizer use to farmers through extension programs and demonstrations (Chan, 2015). Since 2000, the Vietnam government launched strategic plans and programs to improve sustainability of production, and transition to organic farming to meet both domestic and export needs. An example is the

*Strategic Program on Development and Utilization of Biotechnology in Agricultural and Rural Development Until 2020* launched in 2006 to promote the use of organic inputs including biofertilizers and biopesticides. This was followed by the enacting of different policy frameworks with regulations on production, distribution and implementation of such bio-inputs (FAO, 2013). Similarly, the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF) has started initiatives to promote organic agriculture and adoption of biofertilizers as a sustainable alternative to chemical inputs. This move was driven by the increase in the local and international markets for 'chemical-free' crop produce, with immense support from agricultural companies, research institutions and donor agencies. MAFF has since spearheaded research activities including field trials through local universities and farmer groups, to demonstrate the effectiveness of biofertilizers in improving crop yield and farmers' income (MAFF, 2015). In Thailand, the farmers together with local NGOs were given political space since the 1980s, to establish alternative agricultural movements such as the Alternative Agriculture Network (AAN) (Castella & Kibler, 2015). This initiative on alternative agricultural practices, which include the use of biofertilizers, was introduced with the common objective of providing economic and ecological benefits such us improvement of soil quality to produce healthy foods and protect the environment (Ngampimol & Kunathiga, 2008). On the other hand, in Myanmar and Lao PDR, smallholder farmers grow their crops with no inoculation and minimal fertilizer inputs as chemical fertilizers are costly and not readily available, resulting in very poor yields (Rao et al., 2011). The main constraints for biofertilizer production include the lack of qualified personnel and production capacity. Farmers and distributors are also generally not enthusiastic or aware of the importance of this technology, resulting in low supply and adoption of biofertilizers (Su et al., 2002).

## 4. Beneficial microorganisms for biofertilizers

Beneficial microorganisms found in the soils and plant rhizosphere significantly contribute to soil health and plant growth *via* different processes such as BNF, P-solubilization, production of plant growth-promoting substances (antibiotics, metabolites, hormones etc.), decomposition of organic matter, degradation of pollutants etc. Microorganisms also help to reduce plant diseases by out-competing soil-borne pathogens and improve soil structure and soil water holding capacity by producing substances such as polysaccharides which hold soil aggregates together (Patil & Solanki, 2016). Formulation of these beneficial microorganisms into microbial inoculants constitute an important component of integrated nutrient management to increase crop productivity (Chen, 2006). Beneficial microorganisms also called Plant Growth Promoting Rhizo-microorganisms (PGPR) can be broadly divided into two categories: (i) the symbiotic microorganisms such as rhizobia or Arbuscular Mycorrhiza fungi (AMF) which are responsible for mutualistic interactions involving intimate and obligate interactions with a restricted range of host plants; and (ii) the free-living microorganisms that can directly or indirectly stimulate the growth of the plant while living in its rhizosphere (Hinsinger et al., 2018).

Legume inoculation with rhizobia has the longest history of successful biofertilizer use in agriculture. Rhizobia have the unique ability to fix atmospheric $N_2$ through BNF after entering symbiosis with legume species (Sprent, 2001; Willems, 2006). Although rhizobia-legume interaction is quite specific, it is well known to improve plant N uptake, translating to improved plant growth and yield (Pankievicz et al., 2019). Other N-fixing bacteria (so-called free-living N fixing bacteria, such as *Azotobacter*, *Azospirillum* and *Azomonas*) are able to fix $N_2$ without symbiotic association with the plants and thus, can be used to improve the N nutrition of non-legume crops. However, their efficiency is general lower than that of rhizobia (Lesueur et al., 2016) and inoculants containing free-living N fixing bacteria are not widely used in the GMR.

Other microorganisms such as P-solubilizing bacteria (PSB) and AMF have been increasingly studied for they ability to access insoluble P compounds in soils, thus making them available to plants. Many different strains have been identified as PSB, but the most commonly used for biofertilizers include species of *Bacillus*, *Pseudomonas*, *Paenibacillus* and *Burkholderia*. Species of *Enterobacter*, *Arthrobacter*, *Streptomyces* and *Serratia* are also increasingly used for biofertilizers production (Herrmann et al., 2015). AMF are ubiquitous soil microorganisms known to be obligate symbionts (thus unable to complete their life cycle without association with a plant host). They associate with a wide majority of plants, including most commercial crops, and are found in most ecosystems. They notably help to increase the uptake of nutrients (P in particular) but they also interact with the physical, chemical and biological properties of soils through various mechanisms (Herrmann et al., 2015; Lesueur et al., 2016; van der Heijden et al., 2015). As a result, they are of particular interest for the development of new biofertilizers. Other PGPR affect plant growth and development, directly or indirectly, either by facilitating macro- or micro-nutrient uptake by plants, synthesizing phytohormones (auxin, cytokinin) to enhance root growth, or reducing the effects of harmful pathogens by producing siderophores and antimicrobial metabolites (Bashan et al. 2014). Examples include *Alcaligenes*, *Aspergillus*, *Bacillus*, *Klebsiella*, *Lactobacillus* and *Trichoderma*, among others.

In China, research on biofertilizers began in 1958 with the collection, isolation and screening of rhizobia strains for legume inoculation. The most effective strains have been deposited at the Culture Collection and Research Center (CCRC) of the Food Industry Research and Development Institute (CCRC, 1991) and obtained certification for biofertilizer production. Researchers in China later focused on evaluating the effects of single and mixed inoculations with rhizobia, PSB, AMF and other PGPR, recording increased yields of up to 134% along with significant results on soil health and crop quality (Chang & Young, 1999; Liou & Young, 2002; Young, 1990, 2007; Young et al., 1988). To date, above 90% of the biofertilizers available in China contain one or several strains of PSB and/or PGPR e.g. *Bacillus* sp., *Pseudomonas* sp., *Streptomyces* sp., *Azospirillum* sp. etc.

In Myanmar, the market of biofertilizers is not highly developed; legume inoculants (produced by the Department of Agriculture (DAR)) represent the large majority of the products that are available to date. Over the last couple of decades, most of the research has been conducted on the selection of rhizobia strains and production of inoculants for a variety of legumes including soybean, chickpea, pigeon pea and groundnut (ACIAR report, 2019). A few studies assessed the effects of rhizobia isolates in association with PGPR such as *Streptomyces* sp. and reported significant synergistic effects on growth and yield of soybean (Soe & Yamakawa, 2013). DAR has also been producing a small volume of biofertilizers containing *Trichoderma harzianum* for use in integrated disease management in the soil and on decaying plant residues, as well as AMF-containing inoculants, highlighting the growing interest for other types of biofertilizers (Maw et al., 2003; Than & San, 2006).

In Thailand, research on biofertilizers has also increasingly centred on the concept of co-inoculation in order to optimize the efficiency of inoculated strains on crop health, growth and yield (Yuttavanichakul et al., 2012; Aung et al., 2013; Tittabutr et al. 2013). Biofertilizers containing rhizobia strains combined with one or several isolates of PGPR were recently described as ‘supreme’ inoculants, showing the most promising results for development and formulation of new commercial products (Prakamhang et al., 2015). Although some biofertilizers are currently produced and sold by private companies, several units of production belong to research institutions and are project-funded (ACIAR report, 2019). As a result, production volumes are low, with inconsistent supplies (sometimes discontinued), thus not available to farmers when needed. A similar situation was observed in Vietnam where the production of biofertilizers is mainly managed by national universities/research institutes with a limited involvement of the private sector. Vietnam's collection of beneficial microorganisms includes over 500 strains, with strains of *Rhizobium, Azospirillum, Azotobacter, Agrobacterium, Anthrobacter, Flavobacterium, Serratia, Klebsiella, Enterobacter, Bacillus, Pseudomonas, Candida, Trichoderma, Chaetomium, Penicillium, Aspergillus*, among others (Van Toan, 2016). Research on beneficial microorganisms has resulted in the addition of 30 to 50 strains to the repository every year (Nguyen, 2015) and several biofertilizers containing rhizobia, PSB and other PGPR have been developed. However, their production has only been done at a small scale, mainly due to limited resources of the research projects and the small involvement of the private sector, resulting in a low level of adoption of these technologies by farmers.

## 5. Market assessment of biofertilizers in the GMR

The global market for biofertilizers was estimated to exceed US$ 10.2 billion, in 2015, with Europe and Latin America being the top consumers due to the stringent regulations imposed on chemical fertilizers, followed by Asia-Pacific which controlled 34% of the market in 2011 (Masso et al., 2015; Raja, 2013). In Asia, biofertilizer technologies are at various stages of development, testing and adoption. Some Asian countries including China, South Korea, Japan and Taiwan have reported significant breakthroughs in the development, commercialization and adoption on effective biofertilizers (Young, 2007). In China, effort has been put in producing and distributing high quality inoculants for improved and quality crop yield. A significant increase in demand has been observed since the Action plan publication in 2015; with the number of newly approved biofertilizers doubling during the same period, from 9 million tons in 2011 to 20 million tons in 2018 (www.biofertilizer95.cn). More than 6800 products are currently registered in China, of which more than 50% have been registered after 2012. More than 2200 companies are producing and/or selling biofertilizers, and the annual production value has been estimated at approximately 6 billion USD (Dr Zhiyong and Dr Li, *pers. comm.*).

The most common microorganisms found in biofertilizers produced in China belong to the genera *Bacillus*, present in 75% of the products, while the other strains are only found in a limited number of products (<200). Biofertilizer formulations can range from single-strain product to multiple-strain in different carriers; solid formulations (powder and granules) being more popular than liquids (Fang, 2018). Surprisingly, rhizobia inoculants registered at the time were only 58 out of the 6800 registered biofertilizers accounting for only about 1% of the total production of biofertilizers. The low number of biofertilizers for legumes may be linked to the limited level of production in the country as compared to other crops such as maize, rice, vegetables and wheat (FAOSTAT 2019). Available rhizobia inoculants are mainly produced for soybean, peanuts and Chinese milkvetch. Because of the low specificity of PSB and other free living PGPR, the list targeted crops for the registered biofertilizers include a large number of crops, including vegetables, fruit trees, cereals, tobacco, cotton, sugar cane, tea, flowers, herbs and spices, medicinal plants, trees for timber production etc.

A market assessment done by CIAT-Asia in 2019 surveyed and interviewed several companies involved in the production and distribution of biofertilizers in Vietnam (ACIAR report, 2019). The report recorded a current annual production of about 400,000 tons of biofertilizers from 31 interviewed companies. The production capacity of most of the enterprises was reported as <5,000 tons year$^{-1}$ with only a few large-scale companies having an output of <20,000 tons year$^{-1}$. Targeted crops include rice, corn, peanut, vegetables, tea, coffee, rubber tree, cassava, pepper, potato and fruits. As universities and other research institutes are handling the largest part of the biofertilizer production, farmers have limited access to the technologies, resulting in a low level of adoption.

In Myanmar, with the financial support of Australia (ACIAR), the Department of Agricultural Research (DAR) together with the Myanmar Agricultural Service (MAS) established a Rhizobium Unit to produce and distribute rhizobia inoculants to the farmers. However, the production levels have been low due to limited resources and technologies for quality assurance (Herridge et al., 2008). In 2007, the production of rhizobia inoculants in the unit was about 100,000 packets/year but the quality was poor and it was estimated that this volume of biofertilizers would be sufficient to inoculate only <5% of the total legumes grown in the CDZ (Herridge et al., 2008). Production capacity and quality controls have been improved in the past decade, and in 2018, the unit has produced more than 250,000 packets annually of high quality peat-based rhizobia inoculants for seven main legumes crops grown in the country (ACIAR report, 2019). There is, to date, no private company commercializing rhizobia inoculants and, as mentioned before, there is, to our knowledge, limited PGPR- or AMF-based biofertilizers commercially available in Myanmar. It is important to point out that opportunities for development and commercialization of such biofertilizers are huge but will also require a strong investment in terms of research, testing, and farmers' education.

Thailand has been reported to achieve huge increase in the use of biofertilizers primarily through the support from the Ministry of Agriculture and through partnerships with the private sector to develop new products and increase export volumes of biofertilizers to the global markets (Kannaiyan, 2003; Masso et al., 2015). However, the private sector still plays a minor role in comparison to the national institutions. For instance, the Soil Biotechnology unit of the Land Development Department (LDD) is responsible for developing and distributing different types of biofertilizers. LDD produces eight products acclaimed to contain efficient microorganisms with different functions such as N and P nutrition, control of plant pathogens, cellulose decomposition and wastewater treatment (LDD, 2019). These microorganisms mainly include *Trichoderma, Rhizobium*, PSB, lactic acid, acetic acid, proteolytic, cellulose and lipid-degrading bacteria, as well as cellulolytic fungi and yeast. A large part of the biofertilizer production in Thailand is also done at the university level mainly for the research studies or royal projects but are not readily available in the market. Some biofertilizers are only produced biofertilizers on farmers' request or for research purposes as these products have not been registered as commercial products (Dr Tittabutr, Dr Shutsrirung, *pers. comm.*).

The Cambodian biofertilizer market is still not popular. It explains why there are a limited number of companies with products available in the market (Dr Srean, University of Battambang, *pers. comm.*). Some of these biofertilizers are either produced locally or imported from Thailand and Japan. In Lao PDR, a project known as PROFIL did a survey on various agricultural inputs, including biofertilizers, produced and sold in Lao PDR market (Roder et al., 2005). This report stated that in the 1990s, Lao PDR established seven biofertilizer factories, which led to an increase in production levels of biofertilizers to about 2000 tons by 2004. However, these products have not proved to result in significant effects, and interest in the technology has decreased despite being promoted as a tool for "chemical free agriculture" (Roder et al., 2005). Since then, there is little information on further prospects and developments of biofertilizers in Lao PDR. However, in 2020, a new local company called Gaia Vita, working with the French group Biopost-Cofuna, has started commercializing a new biofertilizer made from locally sourced organic matter. It will be interesting to follow up the demand on such biofertilizer in the coming years for getting some ideas about the future of biofertilizers in this country.

## 5. Quality Control

Biofertilizers' quality is one of the key issues in achieving better crop performance and increasing the level of adoption. Use of biofertilizers with inconsistent quality may result in varying effects on crops and as a result, farmers are likely to lose confidence in the products and the technology in general (Husen et al., 2007; Vessey, 2003).

To avoid the poor quality biofertilizers from reaching the market, a quality assurance system must be in place throughout the production process to ensure that the formulation is environmentally friendly (i.e. absence of human and plant pathogens) and provides a protective environment for the microorganisms (composition, pH, water content), thus preventing the decline of their population during storage and transport. In addition, quality control of the final products must be performed by independent laboratories to ensure the standards defined at the national or international level with regards to product quality (number of viable cells, absence of significant contamination, shelf life), safety (absence of pathogens, proper packaging, user instructions) and efficacy are met (Banayo et al., 2001; Desyane, 2012; Herridge et al., 2002; Masso et al., 2015; Herrmann & Lesueur, 2013; Lupwayi et al., 2000). National standards for inoculant quality are not always available in all countries. Available regulations are mainly targeting rhizobia products, vary greatly from country to country and are not strictly enforced (Herrmann & Lesueur, 2013). For instance, the number of viable cells seed$^{-1}$ ranges from 500 to $10^6$ depending on the country. Similarly, the minimum level of contaminants is highly variable from one country to another. Contaminants, in this case, refer to microorganisms that may be present in a product besides the strain(s) of interest and can either be non-pathogenic, plants or human pathogens. In France, biofertilizers should be free of any contaminants (even during storage) while Thailand allows the use of non sterile carriers (Herrmann & Lesueur, 2013).

To date, a big percentage of biofertilizers available worldwide have been shown to be of extremely poor quality thus highly unreliable under field conditions (Herridge et al., 2008; Herrmann et al., 2015; Okon & Itzigsohn, 1995; Tarbell & Koske, 2007). Biofertilizer manufacturers are often not willing to improve their quality assurance system mostly because of the investment it requires, as well as lack of knowledge and facilities (Herrmann & Lesueur, 2013; Lupwayi et al., 2000). In the GMR, the quality and the level of adoption of the biofertilizers remain low and better-quality control systems are mandatory to ensure that efficacious products reach the end users while low-quality inoculants are removed from the market.

Amongst the six GMR countries, China has the most elaborate system for registration and quality control of both strains and biofertilizers. Candidate strains must be identified, tested and registered before being used for biofertilizer formulation and production. Biofertilizer products must also go through field-testing as well as quality and safety checks before they are issued with a generic name and released to the market. In Vietnam, several decrees were passed in 2006 to set up regulatory laws including decrees requiring labelling of commercial products and regulating the production and commercialization (including import and export) of biofertilizers (Van Toan, 2016). The Law on Quality of Commercial Products published in 2008 also indirectly regulates the quality requirements and standards of biofertilizers (Van Toan, 2016). However, even with these regulatory standards in place, improvements are needed in the process of quality assurance and control frameworks. For instance, Van Toan (2016) reported that most of the biofertilizers in Vietnam are not produced in sterile conditions that results in low quality products. In Myanmar, the registration and quality control of rhizobia inoculants produced by the DAR (sole source of inoculants in Myanmar) are performed in accordance with the Fertilizer Control Order of 1985. A quality assurance system is also in place to assess inoculant quality throughout production (Than & San, 2006). The quality control program in Thailand is not mandatory and mainly targets rhizobia products. Tests are performed by independent laboratories on a voluntary basis, following a relative standard number of rhizobia cells per seed of about $10^5$ to $10^6$ cells seed$^{-1}$ (Herridge, 2008; Herrmann & Lesueur, 2013). The process of regulation, registration and quality control of biofertilizers has not been put in place by the government of Cambodia. So far, there is only detailed provisions published as the Law on The Management of Pesticides and Biofertilizers. A similar situation has also been reported in Lao PDR, where no information was found on the quality control systems put in place for development and production on biofertilizers.

## 6. Conclusion and Recommendations

GMR countries have been engaging in agriculture by mainly applying conventional management practices that are often input-intensive resulting in environmental degradation and loss of biodiversity. Chemical inputs-fed systems have been one of the enabling and mostly overlooked factors in the huge increase in food production in the past five decades, yet the biological and environmental consequences of their use are substantial. Over-dependence on chemical fertilizers to meet the current food demand for the growing population has led to an influx of such chemical inputs in the market, with China, Vietnam and Thailand recording high amounts of fertilizer use. On the other hand, Myanmar, Cambodia and Lao PDR record low use of fertilizer and low soil nutrients hence low crop yields.

Agroecological practices have been receiving increasing attention to counteract the negative effects of conventional practices. Adoption of agroecological technologies such as biofertilizers is on the rise at varying paces in every GMR country, with the respective government agencies pushing for investments in the development, distribution and adoption of such bio-inputs. Biofertilizers are low-cost inputs with significant environmentally friendly benefits, great potential in enhancing crop productivity and a viable alternative to high chemical inputs. Beneficial microbes formulated into biofertilizers have been studied over time for their capability to provide essential crop nutrients and improve plant health and growth. Currently, biofertilizers have emerged as an integral component of agroecology and their successful adoption has been reported globally, therefore it is reasonable to anticipate similar success stories in the GMR.

Legume production forms a big part of the GMR’s crop production, with a potential to achieve increased productivity by inoculating the legume crops with low-cost rhizobia biofertilizer for improved N nutrition. Legume inoculants remain underutilized in the region due to technical, social, and institutional constraints as highlighted in this study, with only a small portion of products available in the market. These constraints to the development and adoption of these inoculants need to be addressed including farmers' acceptability of the technology, resources for research and development, limited research and quality control systems.

Biofertilizer demand and production in China are by far the highest of the GMR countries. However, there is still room for product improvement and market expansion, considering the vast agricultural land area, variety of crops and environmental conditions (soil types, climate etc.). The number of biofertilizers produced and marketed in China has tripled over the past two decades. There is, however, limited diversity in the microbial composition, with more than 90% of the biofertilizers mainly containing a mix of *Bacillus* strains. Surprisingly, only 1% of registered products contain rhizobia strain(s) and there is a great need to promote the use of rhizobia inoculants and BNF in the Chinese legume-based cropping systems.

In the rest of the GMR, agriculture still relies on mineral fertilizers and there is so far, limited information on the nature, quality and market of biofertilizers in these countries. In many cases, several elite strains have been isolated and screened but the development and scaling out of these products to the farmers is still low. The research institutions end up keeping these technologies at project levels, while the chief beneficiary – the farmer- is ultimately left out.

Low market and adoption of biofertilizers has been reported in Cambodia and Lao PDR. The farmers have also reported little effect of biofertilizers, so far produced; on yield hence, they start avoiding using these inputs and opt for chemical fertilizers. There was also no information or proper systems on the regulation and quality control put in place for development and production on biofertilizers in these two countries. However, Cambodia's government development plan is to increase the production of legumes such as mung bean and soybean coupled with promotion of development and adoption of legume inoculants. The success of this plan will be a huge step in achieving increased diversification and adoption of legume crops to supplement the well-established rice and cassava crops.

Beneficial aspects and potential of biofertilizer use can be advocated as a potent alternative that not only can feed the emerging population, but also can save the agriculture from the severity of various environmental stresses. Nonetheless, it should be noted that even though the adoption of biofertilizers is significantly increasing, the technology is still nascent and evolving. Therefore, innovative strategies and extensive research on selecting beneficial microbes, their functions and applications should be channelled through advanced and improved techniques. There are vast opportunities for developing and utilizing biofertilizers in the GMR, thus strategic initiatives could focus on, but not limited to;

- Selection and evaluation of effective strains in the field, under different conditions (climate, soil, etc.) to assess potential for optimum and sustainable yields and environmental benefits;
- Extensive research on improved inoculant formulations, shelf-life, residual benefits, persistence and stress adaptations of microbial strains;
- Quality control all the stages from production, distribution and field application by enforcing stringent guidelines and regulations;
- Promotion/integration of biofertilizer use together with other agroecological practices tailored for different cropping systems to achieve sustainable agriculture;
- Capacity building to disseminate these microbial technologies to research and learning institutions, government agencies, private organizations and farmer groups;
- Establishing a network of partners involving local institutions, ministries, private sector and research organizations that can develop an effective model on production of biofertilizers from isolation in the laboratory, on-farm demonstration and training programs, production, scaling up and adoption of biofertilizer technology.

As the demand for organic produce and sustainable agriculture in general is on the rise, there are great opportunities to develop, establish and promote agroecological practices in the region. Biofertilizers can play a key role in the achievement of this goal, in combination with agroecological practices. Nevertheless, to be successful, there is need for more research in formulating, testing and adoption of high-quality products, as well as a strong and effective private sector engagement.

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