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2. Executive summary

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 of soil fertility and sustainability, increases of occurrence of pests and diseases, thus leading to lower ecosystem productivity and income. In this region, further dependence on chemical fertilizers to provide plant nutrients will 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 to support plant nutrition and soil health and have emerged as a potential alternative 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. The project 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.

3. Introduction

3.1 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 3261.6 billion people (ADB, 2012). The countries that make up the GMR include the People's Republic of China, Myanmar, Lao People's Democratic Republic (Lao PDR), Vietnam, Thailand and Cambodia (Fig. 1). While increasingly being industrialized, the GMR predominantly engages in agriculture, mainly carried out by the population in the rural areas (Ingalls et al., 2018). Approximately 75% of the population in the GMR is involved in agriculture, with the Mekong River offering potential for irrigation and continuous expansion in crop production. Agricultural area exceeds 5.8 million km^2 in the GMR countries (Table 1), devoted to the production of rice, sugar cane, maize, oil palm, natural rubber, coconut, fruits, vegetables, tubers etc. (ADB, 2018; 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. Source: ADB 2012.

Table 1. Contextual indicators in the GMR countries (2015).

	GDP per capita US ($)	Population (millions)	Rural population (%)	Total land area (km2)	Agricultural land (km2)	Agricultural land per capita (ha)
China	8,069	1,371	44.5	9,388,210	5,277,330	0.10
Vietnam	2,065	91.7	66.4	310,070	108,737	0.12
Thailand	5,846	68	49.6	510,890	221,100	0.33
Cambodia	1,163	15.6	79.3	176,520	54,550	0.36
Myanmar	1,139	53.9	65.9	653,080	126,450	0.24
Lao PDR	2,159	6.8	61.4	230,800	23,690	0.35

Note: GDP per capita measured in current 2015 USD. Source: OECD/FAO (2017)

3.2 Crop production

3.2.1 Main crops

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 being the first exporter of rice in 2016 (OECD/FAO, 2017). Rice has remained to be the staple food in the GMR for well over 4,000 years, providing at least 50% percent calories in the population's diet (ADB, 2018; Manzanilla et al., 2011; Redfern et al., 2012).

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 for a total production of approximately 60 million tons (20% of the world production) (OECD/FAO, 2017). A variety of other crops are of importance for specific countries in the region. For instance, maize and wheat are top crops 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 tree are very important in Thailand, with a production of about 15 million tons per year, while coffee plantations cover more than 600,000 ha in Vietnam (OECD/FAO, 2017). Advanced farming systems and fertile lands in Thailand has made it the biggest producer and exporter of crop produce in the GMR, and globally known for the quality of its rice and fruits, and as a leading global supplier of rubber (ADB, 2018).

The agriculture sector in Vietnam and Cambodia has gone through significant improvement over the past three decades. Vietnam has become a leading exporter of coffee, pepper, cassava, and rubber, with the government shifting attention to sustainable use of land and water resources and improving food safety, while Cambodia is currently putting more emphasis on other profitable crops such as cassava, maize, mung bean, peanut, soybean, sesame or vegetables (ADB, 2018) thanks to the crop diversification program initiated in the early 2000s.

In Lao PDR, about 77% of the population resides in the rural areas, mainly engaging in rice-based agriculture (especially sticky rice) as the main crop grown in about 75% of its arable land. Other crops include sugarcane, maize, cassava, coffee, tea, and tobacco (ADB, 2018).

In Myanmar, farming is the backbone of the economy, employing ~70% of the country's labour force and providing a major source of export earnings, with China and Thailand providing key regional markets for Myanmar's agricultural produce (ADB, 2018). A big percentage of the population reside in the rural areas (more than 60% of the workforce) and is predominantly engaged in agriculture from crop production, livestock, forestry and fishery (ACIAR, 2018). Grain production is the main cropping practice in Myanmar dominated by rice, followed by pulse and oilseed legumes as well as other non-legume oilseeds (FAOSTAT, 2019; MOALI, 2016). Rice production is concentrated on the Southern region, while other major upland crops (pulses and oilseeds) mainly grown in the Central Dry Zone (CDZ) (Herridge et al., 2019). However, agriculture in the CDZ has been underperforming in the past five decades and reported to be the most food-insecure, water-stressed, climate-sensitive, natural resource-poor and least-developed area of the country (ADB, 2016). Myanmar exported more than US$3 billion worth of agricultural produce in 2016, contributing to about 24% of the GDP and 25% of export earnings. Efforts to increase the productivity of farmlands in Myanmar can enhance its potential to become one of the top global food suppliers as it is currently the world's second largest pulse exporter (World Bank Group, 2016).

3.2.2 Grain legumes/pulses

Legume crops have played a major role as part of sustainable cropping systems throughout the six countries of the GMR. A wide range 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 6 countries (Table 2) (FAOSTAT, 2019). China is the largest producer of groundnut, but the production exceeded 1.5 million tons on 1 million ha of land in Myanmar, thus rising it to be one the highest grown crops in the country. Groundnut is also the main legume grown in Laos and Vietnam, although the production in these countries is still limited (Table 2) (OECD/FAO, 2017).

Table 2: 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

Mung bean (also called green gram) is a common crop grown in Asia which 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). Legume production is of primary importance particularly in Myanmar as it represents 44% of total crop area compared to just 5–10% for China, Laos or Thailand. This huge difference can be attributed to the volatile export markets and to the large cropping areas in the uplands, which is not suitable for rice production (MOALI, 2016). There are 13 types of legumes mainly concentrated in lower and central areas in Myanmar, that, in addition to groundnut and mung bean, include black gram, black bean, pigeon pea, chickpea, cowpea, and soybean. Pigeon pea production in Myanmar is increasing, with a total production of about 800,000 tons from 658000 ha of land, while lentils and peas harvested area and production are still limited in the region.

3.2.3 Forage legumes

Forage legume production in the GMR countries has constantly been in extremely short supply to meet the ever-increasing demand for animal feed and literature on the adoption successes of these forage legume species in the GMR is limited, with only few reports documenting improved livestock nutrition from this technology. Over the years, several forage legume species have been trialled, introduced and adopted at different scales across the GMR countries including: *Aeschynomene americana cv. Glenn, Arachis pintoi, Calopogonium mucinoides*, *Canavalia* sp., *Centrosema pubescens* (CIAT 15160), *Desmodium* sp., *Gliricidia sepium, Leucaena leucocephala, Lotononis bainesii, Macroptilium atropurpureum, Macroptilium lathyroides*, *Paeraria phaseoloides*, *Stylosanthes guyanensis* (CIAT 184), *Stylosanthes hamata* cv. *verano*, *Stylosanthes humilis*, *Stylosanthes scabra* cv. *seca* etc. (Horne & Stür, 1999; Ibrahim et al., 1997).

For instance, the introduction of the protein legume, *Stylosanthes guianensis* cv. CIAT 184 in Laos has resulted in a significantly reduced time for both feed preparation and pig fattening (Stur & Kopinski, 2010). Similarly, Hare et al. (2013) reported that more than 1000 smallholder farmers from the Northern parts of Thailand and Lao PDR currently produce and export (>95%) seeds of various forage varieties including Ubon stylo (*S. guianensis*). In China, *S. guianensis* has been more expansively adopted, especially in Guangdong and Hainan provinces (Peters et al., 2001). The smallholder farmers have been working together with semi-government companies in the processes of drying and sale of stylo feed, thus generating high returns of about US $140/ton at the time (Guodao & Kerridge, 1997). As a result, more than 6000 ha have been grown annually (Peters et al., 2001). The success from the adoption of this forage legume offered an opportunity to low income Chinese farmers with a feed source for their livestock as well as source of income from feed sales, and this gives an insight on the largely unexplored potential of forage legumes for agro-industrial uses (Peters et al., 2001).

Nevertheless, the adoption of improved forage legume technologies has been slow in the past several decades, and this was accredited to unfavourable policies as well as disconnect between scientific research and knowledge dissemination to farmers (Peters et al., 2001; Schultze-Kraft & Peters, 1997). Population pressure and need for arable land also push livestock farming to marginal lands which are less fertile and mostly acidic, resulting in low quality tropical pastures (Horne & Stuer, 1997). In Myanmar, and in the CDR in particular, crop cultivation does not perform well due to low rainfall, poor soils and steep landscape (Kywe & Aye, 2007). The existing pastures are characterized by low population of legume species (*Clitoria ternatea*, *Vigna pilosa*, *Clitoria mariana*, *Melilotus alba*), low production and quality of forages, and can only meet about 50% of animal feed requirements (Aung San et al. 2000). Improved forage production technologies fitted to country-specific environment are needed to produce more forages of good quality from limited land resources.

3.3 Conventional Agriculture: Current practices in the GMR

Globally, evolving agricultural practices continue to play the main role in feeding the human population and influencing the economic growth of most countries. For centuries, agriculture in the GMR has been practiced using diverse systems of shifting cultivation, tillage, cropping patterns and application of mineral fertilizers (Mathew et al., 2012; Mertz et al., 2009; Ziegler et al., 2011). These systems influence biological, physical and chemical soil properties with significant impacts productivity and sustainability of agricultural practices (Mathew et al., 2012). Nevertheless, population pressure and demand for agricultural land in the GMR countries has led to degradation of the ecosystem from the current management practices resulting to detrimental effects on soil fertility, climate change, crop production and crop health (Fox et al., 2014).

In the GMR countries, conventional agriculture is dominated with application of different types and rates of chemical fertilizers. Fertilizers are additives which contain plant-growth enhancing nutrient elements when added to agricultural land which mainly include nitrogen (N), phosphorous (P) and potassium (K) compounds, and minerals such as boron (B), chlorine (Cl), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), magnesium (Mg), molybdenum (Mo), sulphur (S), and zinc (Zn) (Patil & Solanki, 2016). The most widely used fertilizers are categorized as (a) nitrogenous fertilizers such as synthetic ammonia, nitric acid, ammonium nitrate, urea, etc. and (b) phosphatic fertilizers such as phosphoric acid, ammonium phosphate, normal superphosphate, triple superphosphate, etc. (Patil & Solanki, 2016).

Farming systems in the GMR inevitably require the addition of mineral fertilizers to meet the nutrient needs of crops for improved growth and yield. China, Thailand and Vietnam have recorded high levels of these chemical fertilizer inputs (Table 3). However, the excessive and long-term use of chemical fertilizers is widely criticized for their negative environmental impacts such as poor/infertile soils, air and groundwater pollution from leaching, greenhouse gas emission, decrease of biodiversity etc. (Youssef & Eissa, 2014). Zhen et al. (2006) assessed of sustainability of soil fertility management practices and revealed unbalanced nutrient use in cropping systems with excessive use of N and P fertilizers while organic fertilizers are applied in insufficient quantities in China. Chemical fertilizer use in China has since increased to up to 600 kg ha^{-1} per year over the last couple of decades (Yang et al., 2018). In Vietnam, from 1995 to 2000, the amount of fertilizers used per year increased by 7% (N), 8% (P) and 10% (K) and continuing industrial production of fertilizers still insufficient to meet crop nutrients demand (Barrett & Marsh, 2001). On the contrary, Myanmar and Cambodia have reported low levels of N, P and K fertilizers application over time (Table 3), attributed to economic challenges as most smallholder farmers cannot afford these inputs (FAOSTAT, 2019).

Table 3. Mineral fertilizer consumption in the GMR (2016).

	Fertilizer consumption (kg/ha/year)	Nitrogen (N) (Tons)	Phosphate (P_2O_5) (Tons)	Potash (K_2O) (Tons)
China	503.32	30,462,000	15,657,000	13,726,000
Vietnam	429.78	1,636,759	803,111	598,960
Thailand	161.71	1,826,981	322,580	568,789
Myanmar	17.87	138,791	31,411	24,758
Cambodia	17.40	55,902	5,867	4327
Lao PDR	n/a	n/a	n/a	n/a

Source: FAOSTAT, 2019; World Bank, 2019

Increasing crop production to meet the growing global demand of food production has led to increased N inputs to cropland with the use of synthetic N fertilizer currently increased by up to eight-fold, a practice that is not economically viable to farmers nor to the environment (Lassaletta et al., 2016). Legume growers in the region still rely on mineral N fertilizers instead of taking advantage of Biological Nitrogen Fixation (BNF) for N nutrition. However, farmers lack knowledge and access to inoculation technology and continue to rely on ammonium and urea fertilizers for their legume crops (Geisseler & Scow, 2014). On the other hand, unfavourable economic conditions in some GMR countries such as Myanmar and Cambodia have resulted to severely limited N levels in the soil due to very low levels of N fertilizer application rates. Even if application of urea is increased, this will not be sufficient to solve soil N deficiency in Myanmar for instance (Puka-Bearls, 2018).

Phosphorus (P) is an essential element with a significant role to root development, nutrient uptake, and growth of crops, however most agricultural soils have inadequate amounts of P as it is adsorbed onto the solid phases in the soil in stable/fixed chemical compounds that are least available to crops (Mitran et al., 2018). In China, for instance, most soils have low concentrations of P in the soil solution, which is usually insufficient quantities for optimal plant growth, hence requiring application of chemical P fertilizers in most agricultural areas (Li et al., 2013). However, only up to 20% of P applied is taken up by crops resulting in increased accumulation of P in the soil, a primary cause of eutrophication and water pollution (Zhongwang et al., 2017).

3.4 Agroecology and 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."*

Agroecology emerged in the 1980's and associated practices have been popularized to contribute to sustainable ecosystems as they are linked to various ecological processes such as BNF, nutrient cycling, carbon sequestration, soil health, conservation of water and biodiversity (Wezel et al., 2014). Wezel et al. (2014) described these practices to function in through stages towards sustainable agriculture: (i) efficiency increase - practices that reduce input consumption and improve productivity e.g. fertilizers; (ii) substitution of an input or practice e.g. replacing chemical inputs by bio-inputs, and (iii) redesign - change of the whole cropping system. Agroecological practices 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 GMR, member countries have started advocating for a reduction in the over reliance on chemical inputs with 'environmentally safe' alternatives for sustainable agricultural production. A recent trend of modern biotechnologies is gradually getting global and regional attention as the GMR countries, in the face of climate change and food demand, which are currently focusing on reducing use of chemical inputs, promoting integrated nutrient management, organic farming and sustainable agriculture (Mazid & Khan, 2015). One of the main technologies – biofertilizers – has emerged as priority area because of the growing demand for high crop yields, safe food and agricultural sustainability. These products, which are formulations of beneficial microorganisms in non-toxic carriers, are environmentally friendly and are a potential alternative to chemical fertilizers with a crucial role in soil ecosystems for sustainable agriculture (Alori & Babalola, 2018). Therefore, agricultural researchers have shifted focus to exploring effective biotechnology applications such as the use of biofertilizers for improved plant growth/health and soil fertility (Malusá & Vassilev, 2014). Biofertilizers can be used together with other agroecological practices for maximum benefits, and can be included in crop rotations, different tillage practices, organic amendments in order to restore soil fertility and maintain sustainability of crop production systems (Sahoo et al., 2013).

Over the past two decades, there has been different propositions of the definition of biofertilizer but the definition proposed by Vessey (2003) is one of 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 and 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 capable of nitrogen-fixing, phosphate-solubilizing (bacteria, fungi, or algae), or any other beneficial activity derived from this process (Young, 2007).

Biofertilizers have been proven as an effective and sustainable measure in reducing the negative impacts from chemical fertilizer use by playing a significant role in improving soil fertility (Patil & Solanki, 2016). Biofertilizers contribute to two important processes that influence the fertility of soil i.e. mineralization which is responsible for availing soluble nutrients to the plant by organic matter decomposition; and immobilization which involves conversion of atmospheric nitrogen to ammonium and nitrates for easy uptake by roots of plants (Patil & Solanki, 2016; Paul, 2014). Biofertilizers are low-cost and effective inputs with high agricultural benefits, which need to be popularized within the farming community of the GMR (Nath & Das, 2018).

3.5 Beneficial Microorganisms for Biofertilizer Production

Beneficial microorganisms found in the rhizosphere significantly contribute to soil health *via* different processes such as nutrient cycling, decomposition of organic matter, humus formation etc. (Patil & Solanki, 2016). They play an integral part in agricultural productivity as they function to avail and transform nutrients by converting complex compounds to soluble forms that can be taken up by the roots of plants. Microbial processes are crucial for plant growth and include nitrogen (N)-fixation, phosphate (P)-solubilization, production of plant growth-promoting substances (antibiotics, metabolites, hormones etc.) and degrading of plant and animal tissues as well as pollutants (Patil & Solanki, 2016; Russo et al., 2006). Microorganisms also help to improve soil water holding capacity by producing substances such as polysaccharides which hold soil aggregates together and reduce plant diseases by out-competing soil-borne pathogens (Patil & Solanki, 2016). As a result, they can regulate the dynamics of soil structure and functions and the availability of plant macro- and micro-nutrients.

Beneficial microorganisms can be divided into two categories i.e. the symbiotic microorganisms (such as rhizobia or arbuscular mycorrhiza fungi) which are responsible for mutualistic interactions involving intimate and sometimes obligate interactions with a restricted range of host plants, and the free-living microorganisms, also called Plant Growth Promoting Rhizo-microorganisms (PGPR) that can directly or indirectly stimulate the growth of the plant while living in its rhizosphere (Hinsinger et al., 2018). Formulation of these symbiotic microorganisms and/or PGPR into microbial inoculants constitute an important component of integrated nutrient management to increase crop productivity (Chen, 2006).

N-fixing bacteria are broadly classified into: (i) non-symbiotic bacteria (also called free-living N-fixing bacteria) such as cyanobacteria, *Azospirillum*, *Azotobacter*, *Azomonas* which fix atmospheric nitrogen (N_2) as free-living organisms in the soils (Biswas & Gresshoff, 2014; Dresler-Nurmi et al., 2007) or (ii) symbiotic N-fixing bacteria (*Bradyrhizobium*. *Rhizobium, Mezorhizobium, Ensifer (formerly Sinorhizobium)* or *Bradyrhizobium*) generally referred to as ‘rhizobia’. Rhizobia have the unique ability to form nodules and fix N_2 through biological nitrogen fixation (BNF) after entering symbiosis with legume species (Sprent, 2001; Willems, 2006). Although rhizobia-legume interaction is quite specific, legume inoculation with rhizobia has a long history of successful use in agriculture and is well-known to deliver effective bacterial strains to the crops for improved nitrogen uptake and yield, translating to a cheaper and sustainable source of N as compared to application of mineral N (Buntić et al., 2018; Stagnari et al., 2017).

Phosphorus (P) generally occurs at low concentrations in soils and only a very small fraction is available to plants because of the numerous processes responsible for its sorption or immobilisation. P-solubilizing bacteria (PSB) have been increasingly studied for they ability to access insoluble P compounds, 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*. Other bacterial species such as *Enterobacter*, *Arthrobacter*, *Streptomyces* and *Serratia* are also increasingly used for biofertilizers production (Herrmann et al., 2015). Arbuscular mycorrhizal fungi (AMF) are ubiquitous soil microorganisms playing a key role in plant nutrition though interactions with the physical, chemical and biological properties of soils. Although they are obligate symbionts (thus unable to complete their life cycle without association with a plant host), they are known to 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 with improvement of P nutrition reported as the most beneficial effect of AMF (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 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 (Arora et al., 2011; Bhattacharyya & Jha, 2012; Hafeez et al., 2006; Herrmann & Lesueur, 2013; Vessey, 2003). Examples include *Alcaligenes*, *Aspergillus*; *Bacillus*, *Klebsiella*, *Lactobacillus* and *Trichoderma*, among others.

In addition to the properties and efficiency of the selected strains, a combination of factors must be taken into account in order to reach the optimal performance of the biofertilizers. Firstly, the nature of the strains as well as the quantity of active cells contained in the product must be carefully considered. The product shelf life is also a key factor as the inoculated microorganisms must be able to adjust to their new habitat, compete with the native microbiome for niche and nutrients. This highlights the importance of a strict control of the quality of the products (see section 3.6 for details).

The nature of the crop and of the soils may also affect the efficiency of a particular product. Soil properties, including physical and chemical characteristics are thus of particular importance since they directly affect microorganisms' survival, growth and function. The biological status of the soils i.e. the composition of the native microbiome, and the presence of specific populations of interest in particular, such as native rhizobia or AMF, may severely affect the success of inoculation, even with good quality biofertilizers.

3.6 Quality of Biofertilizers

Biofertilizers' quality is one of the key issues in achieving better crop performance and increasing the level of adoption. Quality assurance must be distinguished from quality control: While quality assurance is internally performed throughout the biofertilizer production, quality control is performed on the final products by independent laboratories to ensure that the quality standards are met (Herrmann & Lesueur, 2013). Both systems are essential to maximize the chances of inoculation success.

Quality assurance system should ensure that the biofertilizer formulation should be environmentally friendly (i.e. absence of human and plant pathogens) and provide a protective environment for the microorganisms (composition, pH, water content), thus preventing the decline of their population during storage and transport. The microorganisms' counts should be high enough (and contaminants kept low) throughout the product shelf life and all instructions concerning storage and application should be clearly presented on the label. Unfortunately, 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) Use of biofertilizers of inconsistent quality may result in inconsistent 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 to reach the market, quality control framework must be well-defined at the national or international level to ensure conformity to prescribed standards, product safety and efficacy (Banayo et al., 2012; Catroux et al., 2001; Desyane, 2012; Herridge et al., 2002; Masso et al., 2015). Participation to a quality control program may be mandatory or voluntary depending on the legislation but the controlled factors generally include the nature and effectiveness of the strain(s), number of viable cells, absence of significant contamination, effective and easy-to-apply formulation, adequate shelf life of the product, proper packaging and instructions for use (Herrmann et al., 2015; Lupwayi et al., 2011; Xavier et al., 2004). However, standards for biofertilizer quality generally concern rhizobial products only, vary greatly from country to country, and are more or less enforced (Jenkins & Grzywacz, 2000; Lupwayi et al., 2000; Stephens & Rask, 2000). More details about the quality control of the biofertilizers for each of the GMR countries can be found in the country profiles (section 4).

To date, a large part of the biofertilizers available worldwide have 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), while in countries where regulations are well enforced, expansion of biofertilizer use has been observed, mainly attributed to a decreased frequency of field failure (Catroux et al., 2001; Date, 2001). In the GMR, the level of adoption of the biofertilizers remains limited 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. In addition, there is a great need for education of both manufacturing workers and farmers to give them knowledge and the appropriate skills to perform a successful crop inoculation, leading to a better acceptance of the technology and a stronger confidence in the available products (Bashan, 1998; Bhattacharyya & Jha, 2012; Kannaiyan, 2003).

4. Biofertilizers Production, Quality Control and Markets in the GMR: Country Profiles

4.1 China

The global movement on modern agroecology spearheaded by national governments and international organizations in the 2000s led to the push initiatives of promoting sustainable land uses such as reduced chemical inputs application to counter the trend of intensification of agriculture (Castella & Kibler, 2015). The Chinese government has made tremendous efforts in the past few decades to increase crop productivity to ensure adequate food supply and self-sufficiency of the growing population (Zhen et al., 2006). In 2015, the Ministry of Agriculture in China published the *Action Plan of Zero Growth on Chemical Fertilizers by 2020* which emphasized the need of China to adjust the fertilizers application structure, increase in application efficiency and development of new fertilizers (Chan, 2015). The action plan from the Agriculture docket in China aims to reduce use of chemical fertilizers by at least 20% by 2020. This initiative came about after China realized the consequences of excessive use chemical fertilizers which had taken a toll on the land leading to low productivity, soil degradation, low fertility, acidification, soil salinization and heavy metal pollution of soils. Farmers in China currently apply approximately 70% more chemical inputs to their crops as compared to the rest of the world (Times, 2017). The central and local government agencies support the use of biofertilizers in order to promote sustainable agriculture. Moreover, the government puts emphasis on quality of these biofertilizers in order to achieve increased and quality yields. Besides production and quality control of the microbial products, the relevant agencies are also in charge of creating awareness of biofertilizer use to farmers through extension programs and demonstrations (Young, 2007).

Academic research

Research on biofertilizers began in 1958 with the collection, isolation and screening of rhizobial strains for legume inoculation. Over the years, effective strains were collected and deposited at the Culture Collection and Research Center (CCRC) of the Food Industry Research and Development Institute (CCRC, 1991). Both fast- and slow-growing rhizobia strains were isolated from soybean, peanut, alfalfa and crotalaria, and screening was undertaken in the field to measure impact on yield (Wu, 1958; Young, 2007). Researchers in China later focused on evaluating the effects of single and mixed inoculations with rhizobia, P-solubilizing bacteria (PSBs) and AMF, recording increased yields of up to 134% (Young, 2007; Young et al., 1988). Since 1990, successful studies have been conducted on various microorganisms (including AMF, PSB and other PGPR) with significant results on soil health and as well as growth and quality of crops (Chang & Young, 1999; Liou & Young, 2002; Young, 1990). The number of strains deposited in the CRRC collection has remained relatively steady until the early 2010s, but is now increasing, with a total of 33 strains being approved during the 2015-2019 period (Dr Ruan, *pers. comm.*).

Market assessment

In China, effort has been put in producing and distributing high quality inoculants to improved and quality crop yield. A significant increase in demand has been observed since the Action plan publication (Fig. 2); resulting in a great increase of the number of newly approved biofertilizers during the same period. 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 Ruan and Dr Li, *pers. comm.*).

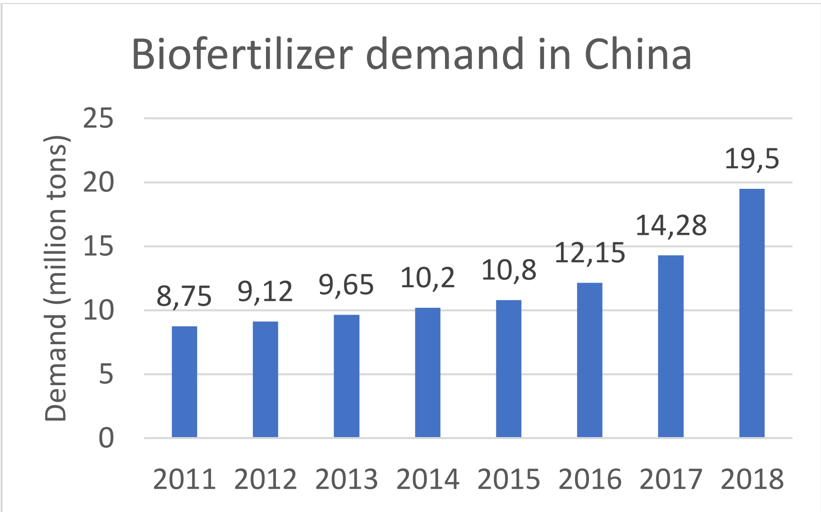

Fig 2. Biofertilizer demand in China since 2011 (www.biofertilizer95.cn).

The most common microorganisms found in the biofertilizers belong to the genera *Bacillus*. *Bacillus* strains are present in 75% of the products while the other strains are only found in a limited number of products (<200, Table 4). 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 (Table 4). 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.

Table 4. Summary of microbial content/products in China.

Microbial composition	No. of products	Microbial composition	No. of products
Bacillus	5192	*Rhodobacter*	4
Lactobacillus	195	*Penicillium*	3
Trichoderma	182	*Rhodopseudomonas*	3
Streptomyces	136	*Thermomyces*	3
Saccharomyces	114	*Azospirillum*	2
Rhizobia	58	*Burkholderia*	2
Aspergillus	45	*Coliformis*	2
Rhodopseudomonas	40	*Glomeromycota*	2
Aspergillus	33	*Myceliophthora*	2
Penicillium	20	*Pasteurella*	2
Pichia	20	*Pediococcus*	2
Pseudomonas	20	*Rhizopus*	2
Beauveria	14	*Chaetomium*	1
Paecilomyces	9	*Geotrichum*	1
Ralstonia	7	*Lactococcus*	1
Candida	5	*Pantoea*	1
Paecilomyces	5	*Rhizoctonia*	1
Pediococcus	4	*Streptococcus*	1

Quality Control

Amongst the GMR countries, China has the most elaborate system for registration and quality control of both strains and biofertilizers. China has established a selection criterion based on technical parameters, testing methods, national and industrial standards, to ensure product quality of biofertilizers before they can be registered and issued with a generic name. As previously mentioned, microbial strains must be identified, characterized and tested before being registered by the CRRC and only registered strains can be used for biofertilizer formulation and production.

With regards to the certification of commercial biofertilizers, China has compiled a series of national standards on product specification, terminology, labeling, testing method, technical specifications for inspection and evaluation. The obtention of the certificate for biofertilizer is a multi-step process that can take up to 3 years and cost more than 5000 US$.

Before an application can be processed, all the strains allegedly contained in the product must be isolated and identified. Standards for the general quality of the product are set based on eight parameters including appearance, cell count, carbon and water content, pH, granule size (for solid products), contamination and shelf life, with the most important parameter being the amount of living cells in the products (Table 5) (Malusá & Vassilev, 2014; Suh et al., 2006). Biofertilizers are also subject to a stringent safety and toxicological evaluation and are tested under field conditions in two different sites and on two different crops (Fang, 2018).

Table 5. Quality criteria required for biofertilizer registration in China.

Formulation	Liquid	Powder	Granular
Appearance	Without strange smell	Brown or black	Black
Viable cell numbers:			
Fast-growing rhizobia	>0.5x10^9/ml	>0.1x10^9/g	>0.1x10^9/g
Slow-growing rhizobia	>1.0x10^9/ml	>0.2x10^9/g	>0.1x10^9/g
Free N-fixing bacteria	>0.5x10^9/ml	>0.1x10^9/g	>0.1x10^9/g
P-solubilizing bacteria			
Organic P	>0.5x10^9/ml	>0.1x10^9/g	>0.1x10^9/g
Inorganic P	>1.5x10^9/ml	>0.3x10^9/g	>0.2x10^9/g
Multi-strain biofertilizer	>1.0x10^9/ml	>0.2x10^9/g	>0.1x10^9/g
Water content (%)		20-35	10
Size (ϕ mm)		0.18	4.5
Organic matter (%C)		>20	>20
pH	5.5-7.0	6.0-7.5	6.0-7.5
Non-target bacteria contamination (%)	<5	<15	<20
Shelf life	>6 months	>6 months	>6 months

Adapted from Suh et al. (2006).

Gaps and future opportunities

The biofertilizer's demand and production in China are by far the highest of the GMR countries. However, there is still room to market increases and improvements, considering the agricultural land area and variety of crops and environmental conditions (soil types, climate etc.). More research is needed to ensure that the right product is applied on the right crop under the right conditions in order to ensure optimal crop performance. There is also a great need for farmers' education with regards to biofertilizers, both in terms of knowledge and application skills.

The number of biofertilizers in China has tripled over the past two decades. There is, however, limited diversity in the microbial composition and multi-strain/ multi-functional biofertilizers, with more than 90% of the biofertilizers mainly containing a mix of *Bacillus* strains.

Surprisingly, only 1% of registered products contain rhizobial strain(s) and serve as inoculants for a limited number of legume species. There is a great need to promote the use of rhizobial biofertilizers in the Chinese legume-based cropping systems, as BNF can be a major component in the improvement of agricultural sustainability (Li et al., 2017). Because of the legume-rhizobia specificity, new rhizobial biofertilizers must be formulated to enhance the field performance of the different legume species grown in China. Other agroecological management practices (rotation, cover crops, intercropping) could then be combined with BNF for maximum benefits to the soil and crop production (Li et al., 2017; Nandwani, 2016).

4.2 Vietnam

The demand for fertilizers in Vietnam is very high as the country has over 10 million ha of agricultural land, translating to an increasing use of mineral fertilizer, with a stagnating low fertilizer use efficiency. For instance, farmers prefer to use chemical N fertilizers for their legume crops at rates of 30–150 kg N/ha over use of legume inoculants as they are readily available thus leading to significant increases in production costs (>$100 million/year) (Herridge et al., 2008). In the Mekong Delta region, the farmers have not fully adopted the practice of inoculating soybean with rhizobial products in order to benefit from economic value of nitrogen supply to the plant from BNF (Thao et al., 2002; Tran, 2004).

After the year 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. For instance, the *Strategic Program on Development and Utilization of Biotechnology in Agricultural and Rural Development Until 2020* was 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 organic products and practices (FAO, 2013).

Academic research

Vietnam has a national collection of beneficial microorganisms at the Soil and Fertilizer Research Institute (SFRI) as well as in collection centres distributed in other research institutions and local universities. The collection centre at SFRI has over 500 strains, with about 30-50 new additions of strains to the repository every year (Nguyen, 2015). The strains in these collection centres include *Rhizobium, Azospirillum, Azotobacter, Agrobacterium, Anthrobacter, Flavobacterium, Serratia, Klebsiella, Enterobacter, Bacillus, Pseudomonas, Candida, Trichoderma, Chaetomium, Penicillum, Aspergillus* etc (Pham, 2016).

The Microbiology Division at SFRI led by Dr Le Thi Thanh Thuy (*pers. comms.*), has run various projects for the past ten years, on biofertilizer development and production, especially on legume inoculants. This unit was able to develop biofertilizers registered and permitted for use in Vietnam, containing N-fixing bacteria, P-solubilizing microorganisms, and other PGPRs. However, these products are not readily available in the market, as the production capacity of the Microbiology Division is limited due to resources and regulations from the government. The products can only be produced at a small scale on request for other projects/institutions (Dr Le *pers. comms*.).

Market assessment

A market assessment done by CIAT-Asia in 2019 surveyed and interviewed several companies involved in the production and distribution of biofertilizers in Vietnam (unpublished data). The report recorded a current annual production of about 400,000 tons of biofertilizers from 31 interviewed companies (Table 6). The production capacity of most of the enterprises is <5,000 tons/year with some large-scale companies having an output of <20,000 tons / year.

Dr Nguyen Khoi Nghia from Can Tho University also provided information on some of the prevalent biofertilizer products in the Mekong Delta region (Table 6) used for different crops grown in the delta including rice, corn, peanut, vegetables, tea, coffee, rubber tree, cassava, pepper, potato and fruits. Additionally, the Soil Microbiology Laboratory at Can Tho University has developed and produces several biofertilizers as listed in Table 6 (Dr Nguyen, *pers. comm.*).

Table 6. Summary of biofertilizer contents in Vietnam.

Microbial composition	No. of products
Bacillus	51
Trichoderma	43
Streptomyces	25
Azotobacter	18
Rhizobia	15
Cellulose-degrading microorganisms (no identification provided)	13
Pseudomonas	13
PSB (no identification provided)	12
Sacharomyces	4
Lactobacillus	4
Actinomyces	3
Azospirillum	3
Aspergillus	2
Candida	2
Burkholderia	2
Paecilomyces	1
Acetobacter	1
Penicillium	1
Lactobacter	1
Thiobacillus	1
Cellulomonas	1
Serratia	1
Endomycorrhiza	1

Quality Control

In 2006, the Vietnam government passed several decrees to set up regulatory laws including decrees requiring labelling of commercial products; regulating the administrative sanctions on production, commercialization and management of fertilizers; trade, import, export and quality control of biofertilizers (Pham, 2016). Contrary to China, the regulatory laws in Vietnam do not directly govern the production and commercialization of biofertilizers. The Law on Quality of Commercial Products, 2008, indirectly regulates the production of biofertilizers through technical regulation and standardization laws (Pham, 2016). The quality requirements of biofertilizers in Vietnam include; density of $\geq 10^8$ CFU/ml beneficial microbes, shelf life of ≥6 months, microbes and carrier used must be safe for humans, animals and the environment, and positive impact on plant growth and yield (Pham, 2016). Even with these regulatory standards in place, Pham (2016) reported that most of the biofertilizers in Vietnam are not produced in sterile conditions as they use simple techniques such as mixing microbial cultures with compost, which results in low quality products.

An ACIAR-funded project in Vietnam reported no commercial rhizobial inoculants in the Vietnam market at the time (Herridge et al., 2008). The project did a survey on some of the legume inoculants produced by key laboratories in the country and reported inconsistencies in the quality of inoculants with varying rhizobial counts and contamination levels within different batches. This is a clear sign that improvements are needed in the process of quality assessment for an effective Quality Assurance program in Vietnam. This project also highlighted the need of technical training to local expertise on inoculant production technologies, resources for infrastructure development, experimental and extension programs to farmers. Additionally, involvement of the private sector is critical for the success of inoculant production and scaling up as private sector partners help to ensure longevity of production and distribution of high legume inoculants in Vietnam (Herridge et al., 2008). Private sector involvement would greatly sustain the production and distribution of biofertilizers as currently most of the production is project-based, carried out by research institutes.

The CIAT-Asia survey in 2018-2019 (unpublished data) reported the international standard ISO 9001 version 2015 (ISO 9001: 2015) is currently widely used in Vietnam, while some companies still use version 2008, ISO 17025: 2017, ISO 22000 etc. (unpublished data). Other companies were reported to comply with national standards of quality control and quality management system as listed on Table 7.

Table 7. Quality control systems are applied by the surveyed companies.

Name of companies	**Quality Control standards**
Dien Trang Company Limited	CASE, Vietcert
Microbiology and Environment Technology Joint Stock Company	TCVN 2003
Tien Nong Industry and Agriculture Joint Stock Company	SO TCCS 15:2016/TN-TH; IQC
Thien Sinh Joint Stock Company	ISO 17025: 2017
Vinh Quang Trading Co., Ltd	TCCS: 02/2008/FITO-CNM GAR
Son Hung Commerce and Service Company Ltd.	ISO 22000
Nicotex Joint Stock Company	TCVN 7185: 2002
Thanh Xuan Limited Liability Company	ISO 14001:2015
Tan Dong Tien Organic Fertilizer Production Limited Company	TCVN LL0 22000:2007; ISO 9001: 200S; HCCP

Gaps and future opportunities

The main cropping systems in Vietnam still rely on mineral fertilizers despite a stagnating fertilizer use efficiency but there is so far, very limited information on the market of legume inoculants in the country. SFRI has the largest collection of agriculturally important strains while some universities and national institutes have also isolated and screened several strains such as Can Tho University and NOMAFSI (Northern mountainous Agriculture and Forestry Science Institute). However, there is still limited number of rhizobia inoculants available in the market. Several products containing other PGPR are being sold in the Vietnam market, but little is known about the quality of these products. There is great potential to develop, establish and improve programs on biofertilizers production as the demand for legume crops is on the rise in this region, at the same time several studies have been isolating and screening effective rhizobia strains for inoculant production.

4.3 Myanmar

Myanmar mainly produces pulses and oilseed legumes after the primary crop – rice, with a production capacity of 5.8 million tons from about 4.2 million ha of arable land (Rao et al., 2011). A previous study by ACIAR reported that the main constraints of legume production in Myanmar include lack of high yielding varieties, good quality inputs and biotic and abiotic stresses affecting the crops. Legumes are mainly grown by smallholder farmers with minimal fertilizer inputs (chemical fertilizers are costly and not readily available) and no rhizobial inoculation. Low production and supply levels of rhizobial inoculants in Myanmar were mainly attributed to the lack of qualified personnel and production capacity (Su et al., 2002). Moreover, other sustainable farming practices such rotation and intercropping have not been extensively adopted by the farmers, resulting in low yields of ~ 1.4 t ha-1 compared to potential yields of 2.0–4.0 t ha-1. Hence improved research and strategic investments in sustainable crop management technologies are needed to improve food production and legume production in particular, livelihoods and income for Myanmar farmers (Rao et al., 2011).

Academic research

The market of legume inoculants in Myanmar is not highly developed with the Department of Agriculture (DAR) producing and distributing most of the rhizobial inoculants for the main legume crops grown in the country. To our knowledge, there is to date, no private companies producing and commercializing biofertilizers (rhizobial or PGPR) in Myanmar.

Most of the research has been conducted on the selection of rhizobial strains for legume inoculation. In 2007, ACIAR commenced a project in Myanmar on rhizobial inoculant technology, with the objective of increasing the production of high-quality rhizobial inoculants through application of a cost-effective strategies, training and extension programs on inoculant technology (Herridge et al. 2008). During this project, high-yielding varieties of chickpea, pigeonpea and groundnut were identified and tested under field conditions in different locations across the CDZ. Identification and testing of new isolates of rhizobial strains were concurrently conducted to optimize crop performance in the different locations. Production of high quality rhizobial inoculants was achieved through infrastructure development and staff and student training.

Other studies have been conducted to assess the effects of *Bradyrhizobium* isolates in association with selected endophytic actinomycetes such as *Streptomyces* sp. and reported significant synergistic effects on growth and yield of legume crops (Soe et al., 2010; Soe et al., 2012; 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 (Maw et al., 2003; Than & San, 2006). Compatibility screening of beneficial actinomycetes with rhizobia strains could also be valuable in formulating highly effective inoculants in Myanmar (Soe et al., 2010).

Market assessment

In Myanmar, the Rhizobium Unit was established by the Department of Agricultural Research (DAR) together with the Myanmar Agricultural Service (MAS) to produce and distribute inoculants to the farmers, but the production levels are still low due to limited resources and technologies for quality assurance (Herridge et al., 2008). In 2007, the production of inoculants in the unit was about 100,000 packets/year but it was estimated that this volume of biofertilizers would be sufficient to inoculate only <5% of the total legumes grown in the CDZ. Since the end of the project in 2018, the unit has produced more than 250,000 packets annually of peat-based rhizobial inoculants for seven main legumes crops grown in the country.

As mentioned before, there is, to our knowledge, no PGPR- or AMF-based biofertilizers commercially available in Myanmar. The 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.

Quality Control

In Myanmar, the registration and quality control of biofertilizers is performed in accordance with the Fertilizer Control Order 1985. Biofertilizer registration consists of several steps including assessing beneficial microbes, cell numbers, nutrient analysis, and field screening of effective strains, for at least one season (Soe et al., 2013). Quality assurance at the Rhizobium unit (DAR) is done by several methods including plant infection count – Most Probable Number (MPN), screening for strain effectiveness and field trials to assess inoculation responses (Than & San, 2006). Quality assessment of the inoculants produced by DAR early in the initial phase of the ACIAR project previously mentioned reported very low numbers of rhizobia and high numbers of contaminants. To counter this problem, ACIAR invested in developing the facilities at DAR and training of local personnel on inoculant production and fermentation technologies. The strategy to improve quality of inoculants involved changes to production protocols, intensive staff training and equipment and facilities renewal, and introduction of exotic rhizobial strains from ICRISAT, Australia and Thailand (Rao et al., 2011). The Australian Quality Assurance procedures were used as model to improve inoculant quality at DAR, including strain verification and maintenance.

Gaps and future opportunities

The amount of chemical fertilizers applied to the fields in GMR has reached millions of tons annually with an equivalent unsustainable expenditure on exhaustible resources for producing these mineral fertilizers. On the contrary, in Myanmar, legumes are mainly grown by small-holder farmers with minimal application of fertilizers resulting to poor yields from low soil nutrients. Previous studies have also reported poor nodulation of several legume species, highlighting the low population of native rhizobia in this region (Herridge et al., 2008).

Herridge et al. (2008) reported that the inoculants produced in Myanmar were of low quality and the production and supply of biofertilizers was limited due to lack of production capacity and personnel expertise, product distribution and storage problems, as well as insufficient education and awareness of farmers of the benefits of inoculation. Although the situation has significantly increased thanks to the ACIAR projects run for the past 10 years, there is still a great need for both research and capacity building to enhance production protocols, implementation of Quality Assurance standards and efficient distribution networks. The adoption of these legume inoculants is still not at the optimal stage as it is restricted to one production unit for the whole country, and the resources are still limited, particularly since the end of the ACIAR project.

The market opportunities for PGPR and AMF inoculants are potentially endless as there is no such biofertilizer currently available in the market for non-legume crops. Identification of potential strains and formulation as well as field testing and commercialization should be prioritized in Myanmar to realize improved crop yield and sustainable agriculture.

4.4 Thailand

In the 1980s, Thai farmers and local NGOs were given political space to establish alternative agricultural movements such as the Alternative Agriculture Network (AAN) (Castella & Kibler, 2015). This initiative on alternative agricultural systems was introduced in Thailand with the common objective of providing economic and ecological benefits such us improvement of soil quality to produce healthy foods and protect the environment and the use of biological products which includes biofertilizers. This program came about from the progressive shift from small scale to large scale farming coupled with application of large amounts of chemical inputs, causing an increase in illnesses and high mortality to farmers, poor soil quality and environmental degradation (Ngampimol & Kunathiga, 2008).

Academic research

The Department of Agriculture in Thailand has a collection of *Bradyrhizobium japonicum* strains (CB1809, USDA110, THA6 and TAL 173), which are commercially used to produce soybean inoculants by various institutions and private companies (Aung et al., 2013; Prakamhang et al., 2015; Tittabutr et al., 2013). Research on beneficial microorganisms and microbial inoculants in Thailand has also centred on the concept of co-inoculation in order to optimize the efficiency of inoculated strains. Prakamhang (2015) described the use and adoption of co-inoculants of PGPR with rhizobia strains as the best strategy in developing ‘supreme’ inoculants (Prakamhang et al., 2015). Yuttavanichakul et al. (2012) also assessed the co-inoculation of rhizobia strains with selected PGPRs isolates including *Bacillus megaterium, B. subtilis, B. subtilis subsp. subtilis,* and *Pseudomonas* sp. to inhibit the growth of root-rot causing fungus, *Aspergillus niger*. Aung et al. (2013) conducted a study on co-inoculation of *Bradyrhizobium japonicum* CB1809 and USDA110 with *Azospirillum* sp. significantly increased dry weight matter of soybean over non-inoculated controls, in both Myanmar and Thailand soils.

Research on beneficial strains for biofertilizer production is also done by learning institutions such as Suranaree University of Technology and Chiang Mai University. SUT has developed and tested inoculants for soybean, mung bean, peanut, and hemp (Dr Tittabutr, *pers. comm.*). The Soil Microbiology Lab at the Faculty of Agriculture at Chiang Mai University has also been conducting research on legume inoculants for soybean, red kidney bean, azuki bean and cowpea for more than two decades while other studies on non-symbiotic diazotrophs and PGPRs have been ongoing for the past 12 years (Dr Shutsrirung, *pers. comm.*). Due to limited resources and manpower, the department has not been able to continue producing biofertilizers and have already lost many good strains (Dr Shutsrirung, *pers. comm.*).

Market assessment

Thailand has been reported to achieve drastic 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). The Land Development Department (LDD) under the Ministry of Agriculture in Thailand has a Soil Biotechnology unit responsible for developing and distributing different types of biofertilizers as well as biocontrol products (Table 8). The LDD products are acclaimed to contain efficient microorganisms with different functions such as N and P nutrition, control of plant pathogens, cellulose decomposition for organic matter and compost and wastewater treatment (LDD, 2019).

Table 8. Biofertilizers produced by the Land Development Department.

Products	Microbial composition	Functions
Super LDD 1	Cellulolytic fungi (4 species) Cellulolytic actinomycetes (2 species) Lipid degrading bacteria (2 species)	Cellulose and lignin decomposition of crop residues to make compost
Super LDD 2	Yeast Lactic acid bacteria Proteolytic bacteria Lipolytic bacteria Phosphate solubilizing bacteria	Activate fermentation and digestion process of organic waste such as residues from fruit, vegetable, fish and snail for producing bio-extract.
Super LDD 3	*Trichoderma* *Bacillus*	Control and inhibit soil borne plant pathogens
LDD 6	Yeast Lactic acid bacteria Proteolytic bacteria Lipolytic bacteria Phosphate solubilizing bacteria	Activate fermentation and digestion of food waste for wastewater treatment in garbage areas
LDD 7	Yeast Acetic acid bacteria Lactic acid bacteria	Produce alcohol and organic acids that acts as biocontrol
LDD 9	Phosphate solubilizing bacteria	Secrete organic acids that dissolve unavailable phosphorus in the soil for plant uptake
LDD 11	*Rhizobium* Phosphate solubilizing bacteria	Biological Nitrogen Fixation Phosphorous solubilization
LDD 12	Not mentioned	Contain microorganisms that can convert insoluble/ inorganic compounds into soluble forms. Produce plant growth hormones

Biofertilizer production in Thailand is also done at institutional level mainly for the research studies or royal projects and are not readily available in the market. For instance, SUT only produces biofertilizers on farmers’ request as these products have not been registered as commercial products (Dr Tittabutr, *pers. comm.*). Chiang Mai University developed a service project known as "Production and Development of Bio-organic Products for Sustainable Agriculture' whose main activity is to produce organic fertilizer and biofertilizers, which were only produced on order or for research purposes, for several projects from the government and the private sector but has since not received any requests in the past few years (Dr Shutsrirung, *pers. comm.*).

Quality Control

The quality control program in Thailand is not mandatory and voluntarily performed by independent laboratories, following a relative standard number of rhizobial cells per seed of about 10^5 to 10^6 cells/seed (Herridge 2008; Herrmann and Lesueur, 2013). Quality control of these inoculants is done at the institution level by Total plate count and MPN to estimate the number of cells (usually around 10^8 cells/ml) before releasing the products to the farmers (Dr Tittabutr *pers. comms.*).

Gaps and future opportunities

Thailand has great potential in improving the adoption and market of biofertilizers especially through the private sector and government research divisions such as the Land Development Department. Thailand faces the same challenge as Vietnam and Myanmar whereby 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. Little is also known about the quality of available products in the biofertilizer market in Thailand. Capacity development, quality control and farmer awareness are some of the key issues that need to be addressed to enable the adoption and use of these products by the farmers.

4.5 Cambodia

Status of biofertilizer development, market and quality control

In Cambodia, the campaign to improve food security and increase farmers' income through crop diversification in the lowland rice-based systems has led to an increase in legumes introduced to the farming system (Kirchhof et al., 2000; Seng et al., 2008). There is immense potential for agricultural intensification achievable through adoption of sustainable technologies, diversification incentives and regional specialization through the support of the national and local governments (World World Bank, 2006).

In the recent past, the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF) started initiatives to promote organic agriculture and adoption of biofertilizers as a sustainable alternative to the over-dependence on 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). However, the process of regulation, registration and quality control of biofertilizers has not been exclusively 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.

Even though the Cambodian biofertilizer market is still not as popular as for mineral fertilizers, there are a limited number of companies whose products are available in the Cambodian market (Dr Srean, University of Battambang, *pers. comm.*). Some of these biofertilizers are either produced locally or imported from Thailand, Japan and the USA including;

- **Sovannaphum Organic Fertilizer** produced and distributed by Bio Organic Fertilizer company in Cambodia.
- **Fertilizer Accelerator** containing Bacteria and fungi; made in Battambang, Cambodia.
- **Angkor Nature Biofertilizer** containing *Azospirilum lipoderum, Bacillus megaterium* var *phosphaticum* and *Frateuria aurantia*
- **Thai Biofertilizers** imported from Thailand by Star Sunshine Co., LTD and sold in Cambodia.
- **Bio Organic Fertilizers** imported from Japan by Five Star International Fertilizer Company (Cambodia).
- **Biofertilizers with Thai technology** containing *Trichoderma.*
- Products from Hi Green Co., Ltd in Cambodia such as **Hi-Green-Mater Trichoderma and Hi-Green-Doctor Root Enhancement**
- **AGN biofertilizers** (mainly containing *Bacillus* strains) were imported from the USA in 2016 for sale in Cambodia but has since stopped importing to the Cambodian market.

Gaps and future opportunities

Low market and adoption of biofertilizers has been reported in Cambodia as the private sector as well as farmers are generally not enthusiastic or aware of the importance of these products. The farmers have also reported little effect of biofertilizers, so far produced, on yield hence they start avoiding to use these inputs and opt for chemical fertilizers. Seng et al. (2008) observed a limited understanding of legume production amongst the farmers in Cambodia, posing a huge challenge in dissemination of these biotechnologies. There was also no information or proper systems on the regulation and quality control put in place for development and production on biofertilizers. However, Cambodia's government development plan is to increase the production of legumes such as mung bean and soybeans 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.

4.6 Lao PDR

Status of biofertilizer development, market and quality control

Agriculture in Lao PDR has grown significantly with the increase in land under cultivation, labour and inputs such as improved seeds and fertilizers (World World Bank, 2006). However, the adoption of biofertilizers in Laos is still limited as the distributors as well as farmers are generally not enthusiastic or aware of the importance of these products. Similar to Cambodia, there is no defined system by the government officially defined for regulation and quality control of biofertilizers.

A report from a project known as PROFIL did a survey of various agricultural inputs produced and sold in the Laos market including soil amendments and fertilizers including biofertilizers (Roder et al., 2005). This report stated that in the 1990s, Lao PDR established 7 biofertilizer factories, with the technical support from Vietnam, which mainly used peat from the lake as the main raw material for the biofertilizers. As a result of the PROFIL project, the production levels of biofertilizers in Laos increased to about 2000 tons by 2004. There were only a few range of products such as AMF, organic fertilizers consisting mainly of peat, Effective Micro-organisms (EM) solution and other beneficial microbes (Roder et al., 2005). However, tests done by Lao-IRRI and a FAO project showed no or little significant effect of these biofertilizers, whereas some farmers reported an effect when the biofertilizer was used in combination with inorganic fertilizers. The companies recorded high sales from these fertilizers because it was promoted far-and-wide using an attractive slogan of promoting “chemical free agriculture” (Roder et al., 2005). Since then, there is little information on further prospects and developments of biofertilizers in Lao PDR.

Some of the reported constraints in adoption of biofertilizers in Lao PDR include high costs of production resulting to expensive products, not affordable to farmers. Moreover, the Lao government still faces some challenges in the effort to promote biofertilizers such as low quality of inputs for bio-fertilizer productions, limited capacity and resources and lack of awareness on sustainable agricultural production to mitigate risks of climate change (Lim et al., 2014). There was also no information/literature found on the quality control systems put in place for development and production on biofertilizers.

5. Conclusions and Recommendations

5.1 Conclusions

GMR countries have been engaging in agriculture by mainly applying conventional management practices which are often input-intensive resulting to 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, other GMR countries such as Cambodia and Myanmar record low use of fertilizer use hence low crop yields.

However, agroecological practices have been receiving increasing attention to counteract the negative effects of current management practices. Adoption of sustainable technologies such as biofertilizers is increasing at varying paces in every GMR country with the respective government continuously pushing for investments in sustainable agriculture to address restoration of nutrient-depleted soils by application of alternative inputs, mainly biofertilizers.

Biofertilizers are low-cost inputs with high environmentally friendly benefits in the agriculture sector, which needs to be popularized in the farming communities in the GMR, for their great potential in enhancing crop productivity and as a viable alternative to chemical inputs. The microbes exploited for use as 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 agriculture 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 with by inoculating the legume crops with low-cost rhizobia biofertilizer for improved N nutrition. Biofertilizers containing P-solubilizers and PGPRs, such as AMF and *Bacillus*-containing inoculants, are also vital in reducing external P-inputs by making the fixed-P available to crops, and improving plant health, respectively. Legume inoculants remain underutilized in the region due to technical, social, and institutional constraints as highlighted in this report, with only a small portion of available products available in the market. These constraints to the development and adoption of these inoculants need to be addressed such as farmers' acceptability of the technology, resources for research and development, limited research and quality control systems.

5.2 Recommendations

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 for optimum and sustainable yields with regards to functions, plant-microbe interactions, target crops and environmental factors;
- 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 which 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.

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