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

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1 **Abstract**

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

26

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

28

29 **1. Introduction**

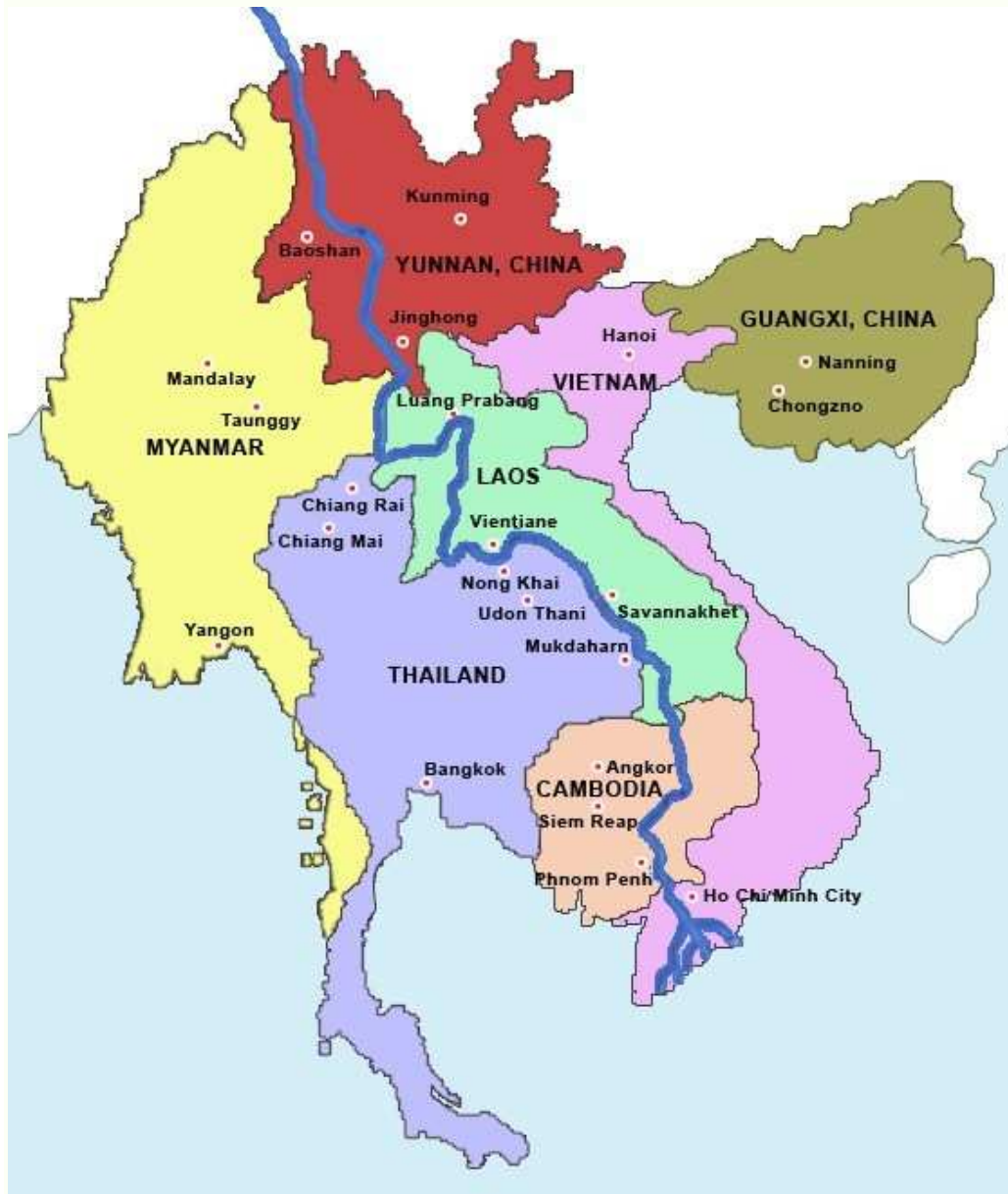
30 Globally, biofertilizer development and use has been on the rise due to the universal problem
31 of environmental degradation from an overuse of chemical fertilizers. Bio-fertilizers, defined
32 as products containing beneficial microorganisms with the potential to improve soil fertility
33 and crop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

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

50

51 **2. Agriculture in the Great Mekong Region**

52 The Great Mekong Region (GMR) is an economic area of six countries connected by the
53 Mekong River, covering an area of about 11.3 million km² and a combined population of 3.3
54 billion people (ADB, 2012). The countries that make up the GMR include the People's
55 Republic of Cambodia, China, Lao People's Democratic Republic (Lao PDR), Myanmar,
56 Thailand and Vietnam (Fig. 1). While increasingly being industrialized, the GMR
57 predominantly engages in agriculture. Agricultural area exceeds 5.8 million km², involving
58 75% of the population, mostly in the rural areas (ADB, 2018; Ingalls et al., 2018;
59 OECD/FAO, 2017; World Bank - World Development Indicators, 2019).



61

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

65

66 Rice is undoubtedly the main crop in the whole region with a production ranging from 4 to
 67 214 million tons, from a harvested area of 1 to 31 million ha (ADB, 2018). The GMR
 68 countries provide more than 40% of the world production of rice, with Thailand reported as
 69 the number one rice exporter in 2016 (OECD/FAO, 2017). Sugar cane is one of the most

70 cultivated crops in the region after rice, with a production of > 100 million tons in Thailand
 71 and China. Similarly, cassava production covers 2.7 million ha across the region with a total
 72 production of approximately 60 million tons (20% of the world production) (OECD/FAO,
 73 2017). Varieties of other crops are of value in specific countries in the region. For instance,
 74 maize and wheat are top crops grown in China (260 million and 134 million tons,
 75 respectively) but their production in the rest of the region is significantly lower. Oil palm and
 76 rubber trees are very important in Thailand, with a production of about 15 million tons per
 77 year (OECD/FAO, 2017). Vietnam has become a leading exporter of coffee, pepper, and
 78 rubber while Cambodia is currently putting more emphasis on other profitable crops such as
 79 legumes and vegetables (ADB, 2018). In Myanmar, top crops include pulse and oilseed
 80 legumes as well as other non-legume oilseeds (FAOSTAT, 2019; MOALI, 2016).

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

91 **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

92 Source: FAOSTAT, 2019

93

94 **1.1 Conventional agriculture and fertilizer use**

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

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

122

123

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

	Fertilizer consumption (kg ha⁻¹ year⁻¹)	Nitrogen (N) (Tons)	Phosphate (P₂O₅) (Tons)	Potash (K₂O) (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

125 Source: FAOSTAT, 2019; World Bank, 2019

126

127 **1.2 Importance of restoring soil health and soil fertility for stopping soil** 128 **degradation**

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

135 In the GMR, soil degradation has become a major constraint due to erosion, depletion of
 136 nutrients and soil organic carbon (SOC), aggravation of soil salinity and acidification, decline
 137 in biodiversity of natural, agricultural, and forest ecosystems (Lal, 2015; Pimentel & Burgess,
 138 2013). Extensive use of heavy doses of mineral fertilizers (such as synthetic ammonia, urea,
 139 ammonium phosphate or triple superphosphate) in industrialized agricultural systems have
 140 further affected soil health through leaching, eutrophication, GHG emission and
 141 environmental pollution (Lal, 2015). Moreover, soil degradation has strong negative
 142 economic impacts since a large part of the population relies on agriculture as a primary
 143 source of income (Lal, 2016). To date, more than 500 million hectares of tropical arable land
 144 and 33% of earth's land surface globally face decline in soil health (Lal, 2015; Lamb et al.,
 145 2005). Restoring the soil fertility of degraded agricultural soils is one of the most-pressing
 146 topics that holds the key to dealing with three main challenges i.e. feeding the growing
 147 population, mitigation of climate change and biodiversity conservation, while achieving a
 148 productive and sustainable system.

149 In the GMR, governmental initiatives are increasingly being developed to reduce the use of
150 chemical fertilizers while ensuring high crop yields and resilience to climate change. For
151 instance, in 2015, the Ministry of Agriculture in China published the *Action Plan of Zero*
152 *Growth on Chemical Fertilizers by 2020* which emphasizes the need of China to adjust the
153 fertilizers application structure, increase in application efficiency and promote alternative
154 practices to drastically reduce the use of mineral fertilizers in agricultural systems (Chan,
155 2015). Several initiatives have also been started in Vietnam, Thailand and Cambodia to
156 promote organic farming and ‘chemical-free’ crop production. Implementation of such
157 agroecological practices may improve soil health by reducing reliance on external inputs and
158 convert low-input systems into productive lands.

159

160 **3. Agroecology: A focus on biofertilizers**

161 The term agroecology is loosely defined to integrate several aspects of achieving an
162 environmentally-friendly and socially-sensitive approaches to agriculture, focusing on
163 production as well as on the ecological sustainability of the production system (Altieri, 2018).
164 The Association of Agroecology Europe outlined a holistic definition of agroecology as
165 follows: “*Agroecology is considered jointly as a science, a practice and a social movement.*
166 *It encompasses the whole food system from the soil to the organization of human societies. As*
167 *a science, it gives priority to action research, holistic and participatory approaches, and*
168 *trans-disciplinarity including different knowledge systems. As a practice, it is based on*
169 *sustainable use of local renewable resources, local farmers’ knowledge and priorities, wise*
170 *use of biodiversity to provide ecosystem services and resilience, and solutions that provide*
171 *multiple benefits (environmental, economic, social) from local to global. As a movement, it*
172 *defends smallholders and family farming, farmers and rural communities, food sovereignty,*
173 *local and short marketing chains, diversity of indigenous seeds and breeds, healthy and*
174 *quality food.” Agroecological practices have been popularized to contribute to sustainable
175 ecosystems as they are linked to various ecological processes such as biological nitrogen
176 fixation (BNF), nutrient cycling, carbon sequestration, soil health, and conservation of water
177 and biodiversity (Wezel et al., 2014). They range from high technology-based practices to
178 ecology-based practices, including no or reduced tillage, cover crops, green manure,
179 intercropping, crop rotations, agroforestry, resource and biodiversity conservation practices,
180 precision farming, genetic engineering and biofertilizer use (Altieri, 2018; Wezel et al.,
181 2014).*

182 In the face of climate change and growing demand for high crop yields, safe food and
183 agricultural sustainability, one of the main technologies in agroecology – biofertilizers – has
184 emerged as priority area in the GMR (Mazid & Khan, 2015). Over the past two decades,
185 there has been different propositions of the definition of biofertilizer. However, the definition
186 proposed by Vessey (2003) has been the most popular. A biofertilizer is thus defined as “*a*
187 *substance which contains living microorganisms which, when applied to seed, plant surfaces,*
188 *or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by*
189 *increasing the supply or availability of primary nutrients to the host plant”*. Another
190 proposition by Fuentes-Ramirez & Caballero-Mellado (2005) later defined biofertilizer as “*a*
191 *product that contains living microorganisms, which exert direct or indirect beneficial effects*
192 *on plant growth and crop yield through different mechanisms”*. Biofertilizers can also be
193 referred to as microbial inoculants, to describe preparations containing live or latent cells of
194 an efficient microbial strain (bacteria, fungi, or algae) capable of nitrogen (N)-fixation,
195 phosphate (P)-solubilization, or any other beneficial activity such as hormone or metabolite
196 production (Young, 2007).

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

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

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

238

239 **4. Beneficial microorganisms for biofertilizers**

240 Beneficial microorganisms found in the soils and plant rhizosphere significantly contribute to
241 soil health and plant growth *via* different processes such as BNF, P-solubilization, production
242 of plant growth-promoting substances (antibiotics, metabolites, hormones etc.),
243 decomposition of organic matter, degradation of pollutants etc. Microorganisms also help to
244 reduce plant diseases by out-competing soil-borne pathogens and improve soil structure and
245 soil water holding capacity by producing substances such as polysaccharides which hold soil
246 aggregates together (Patil & Solanki, 2016). Formulation of these beneficial microorganisms

247 into microbial inoculants constitute an important component of integrated nutrient
248 management to increase crop productivity (Chen, 2006). Beneficial microorganisms also
249 called Plant Growth Promoting Rhizo-microorganisms (PGPR) can be broadly divided into
250 two categories: (i) the symbiotic microorganisms such as rhizobia or Arbuscular Mycorrhiza
251 fungi (AMF) which are responsible for mutualistic interactions involving intimate and
252 obligate interactions with a restricted range of host plants; and (ii) the free-living
253 microorganisms that can directly or indirectly stimulate the growth of the plant while living
254 in its rhizosphere (Hinsinger et al., 2018).

255 Legume inoculation with rhizobia has the longest history of successful biofertilizer use in
256 agriculture. Rhizobia have the unique ability to fix atmospheric N₂ through BNF after
257 entering symbiosis with legume species (Sprent, 2001; Willems, 2006). Although rhizobia-
258 legume interaction is quite specific, it is well known to improve plant N uptake, translating to
259 improved plant growth and yield (Pankiewicz et al., 2019). Other N-fixing bacteria (so-called
260 free-living N fixing bacteria, such as *Azotobacter*, *Azospirillum* and *Azomonas*) are able to fix
261 N₂ without symbiotic association with the plants and thus, can be used to improve the N
262 nutrition of non-legume crops. However, their efficiency is general lower than that of
263 rhizobia (Lesueur et al., 2016) and inoculants containing free-living N fixing bacteria are not
264 widely used in the GMR.

265 Other microorganisms such as P-solubilizing bacteria (PSB) and AMF have been
266 increasingly studied for they ability to access insoluble P compounds in soils, thus making
267 them available to plants. Many different strains have been identified as PSB, but the most
268 commonly used for biofertilizers include species of *Bacillus*, *Pseudomonas*, *Paenibacillus*
269 and *Burkholderia*. Species of *Enterobacter*, *Arthrobacter*, *Streptomyces* and *Serratia* are also
270 increasingly used for biofertilizers production (Herrmann et al., 2015). AMF are ubiquitous
271 soil microorganisms known to be obligate symbionts (thus unable to complete their life cycle
272 without association with a plant host). They associate with a wide majority of plants,
273 including most commercial crops, and are found in most ecosystems. They notably help to
274 increase the uptake of nutrients (P in particular) but they also interact with the physical,
275 chemical and biological properties of soils through various mechanisms (Herrmann et al.,
276 2015; Lesueur et al., 2016; van der Heijden et al., 2015). As a result, they are of particular
277 interest for the development of new biofertilizers. Other PGPR affect plant growth and
278 development, directly or indirectly, either by facilitating macro- or micro-nutrient uptake by

279 plants, synthesizing phytohormones (auxin, cytokinin) to enhance root growth, or reducing
280 the effects of harmful pathogens by producing siderophores and antimicrobial metabolites
281 (Bashan et al. 2014). Examples include *Alcaligenes*, *Aspergillus*, *Bacillus*, *Klebsiella*,
282 *Lactobacillus* and *Trichoderma*, among others.

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

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

304 In Thailand, research on biofertilizers has also increasingly centred on the concept of co-
305 inoculation in order to optimize the efficiency of inoculated strains on crop health, growth
306 and yield (Yuttavanichakul et al., 2012; Aung et al., 2013; Tittabutr et al. 2013). Biofertilizers
307 containing rhizobia strains combined with one or several isolates of PGPR were recently
308 described as ‘supreme’ inoculants, showing the most promising results for development and
309 formulation of new commercial products (Prakamhang et al., 2015). Although some
310 biofertilizers are currently produced and sold by private companies, several units of

311 production belong to research institutions and are project-funded (ACIAR report, 2019). As a
312 result, production volumes are low, with inconsistent supplies (sometimes discontinued), thus
313 not available to farmers when needed. A similar situation was observed in Vietnam where the
314 production of biofertilizers is mainly managed by national universities/research institutes
315 with a limited involvement of the private sector. Vietnam's collection of beneficial
316 microorganisms includes over 500 strains, with strains of *Rhizobium*, *Azospirillum*,
317 *Azotobacter*, *Agrobacterium*, *Anthrobacter*, *Flavobacterium*, *Serratia*, *Klebsiella*,
318 *Enterobacter*, *Bacillus*, *Pseudomonas*, *Candida*, *Trichoderma*, *Chaetomium*, *Penicillium*,
319 *Aspergillus*, among others (Van Toan, 2016). Research on beneficial microorganisms has
320 resulted in the addition of 30 to 50 strains to the repository every year (Nguyen, 2015) and
321 several biofertilizers containing rhizobia, PSB and other PGPR have been developed.
322 However, their production has only been done at a small scale, mainly due to limited
323 resources of the research projects and the small involvement of the private sector, resulting in
324 a low level of adoption of these technologies by farmers.

325

326 **5. Market assessment of biofertilizers in the GMR**

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

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

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

364 In Myanmar, with the financial support of Australia (ACIAR), the Department of
365 Agricultural Research (DAR) together with the Myanmar Agricultural Service (MAS)
366 established a Rhizobium Unit to produce and distribute rhizobia inoculants to the farmers.
367 However, the production levels have been low due to limited resources and technologies for
368 quality assurance (Herridge et al., 2008). In 2007, the production of rhizobia inoculants in the
369 unit was about 100,000 packets/year but the quality was poor and it was estimated that this
370 volume of biofertilizers would be sufficient to inoculate only <5% of the total legumes grown
371 in the CDZ (Herridge et al., 2008). Production capacity and quality controls have been
372 improved in the past decade, and in 2018, the unit has produced more than 250,000 packets
373 annually of high quality peat-based rhizobia inoculants for seven main legumes crops grown

374 in the country (ACIAR report, 2019). There is, to date, no private company commercializing
375 rhizobia inoculants and, as mentioned before, there is, to our knowledge, limited PGPR- or
376 AMF-based biofertilizers commercially available in Myanmar. It is important to point out
377 that opportunities for development and commercialization of such biofertilizers are huge but
378 will also require a strong investment in terms of research, testing, and farmers' education.

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

395 The Cambodian biofertilizer market is still not popular. It explains why there are a limited
396 number of companies with products available in the market (Dr Srean, University of
397 Battambang, *pers. comm.*). Some of these biofertilizers are either produced locally or
398 imported from Thailand and Japan. In Lao PDR, a project known as PROFIL did a survey on
399 various agricultural inputs, including biofertilizers, produced and sold in Lao PDR market
400 (Roder et al., 2005). This report stated that in the 1990s, Lao PDR established seven
401 biofertilizer factories, which led to an increase in production levels of biofertilizers to about
402 2000 tons by 2004. However, these products have not proved to result in significant effects,
403 and interest in the technology has decreased despite being promoted as a tool for "chemical
404 free agriculture" (Roder et al., 2005). Since then, there is little information on further
405 prospects and developments of biofertilizers in Lao PDR. However, in 2020, a new local

406 company called Gaia Vita, working with the French group Biopost-Cofuna, has started
407 commercializing a new biofertilizer made from locally sourced organic matter. It will be
408 interesting to follow up the demand on such biofertilizer in the coming years for getting some
409 ideas about the future of biofertilizers in this country.

410

411 **5. Quality Control**

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

416 To avoid the poor quality biofertilizers from reaching the market, a quality assurance system
417 must be in place throughout the production process to ensure that the formulation is
418 environmentally friendly (i.e. absence of human and plant pathogens) and provides a
419 protective environment for the microorganisms (composition, pH, water content), thus
420 preventing the decline of their population during storage and transport. In addition, quality
421 control of the final products must be performed by independent laboratories to ensure the
422 standards defined at the national or international level with regards to product quality
423 (number of viable cells, absence of significant contamination, shelf life), safety (absence of
424 pathogens, proper packaging, user instructions) and efficacy are met (Banayo et al., 2001;
425 Desyane, 2012; Herridge et al., 2002; Masso et al., 2015; Herrmann & Lesueur, 2013;
426 Lupwayi et al., 2000). National standards for inoculant quality are not always available in all
427 countries. Available regulations are mainly targeting rhizobia products, vary greatly from
428 country to country and are not strictly enforced (Herrmann & Lesueur, 2013). For instance,
429 the number of viable cells seed⁻¹ ranges from 500 to 10⁶ depending on the country. Similarly,
430 the minimum level of contaminants is highly variable from one country to another.
431 Contaminants, in this case, refer to microorganisms that may be present in a product besides
432 the strain(s) of interest and can either be non-pathogenic, plants or human pathogens. In
433 France, biofertilizers should be free of any contaminants (even during storage) while
434 Thailand allows the use of non sterile carriers (Herrmann & Lesueur, 2013).

435 To date, a big percentage of biofertilizers available worldwide have been shown to be of
436 extremely poor quality thus highly unreliable under field conditions (Herridge et al., 2008;
437 Herrmann et al., 2015; Okon & Itzigsohn, 1995; Tarbell & Koske, 2007). Biofertilizer

438 manufacturers are often not willing to improve their quality assurance system mostly because
439 of the investment it requires, as well as lack of knowledge and facilities (Herrmann &
440 Lesueur, 2013; Lupwayi et al., 2000). In the GMR, the quality and the level of adoption of
441 the biofertilizers remain low and better-quality control systems are mandatory to ensure that
442 efficacious products reach the end users while low-quality inoculants are removed from the
443 market.

444 Amongst the six GMR countries, China has the most elaborate system for registration and
445 quality control of both strains and biofertilizers. Candidate strains must be identified, tested
446 and registered before being used for biofertilizer formulation and production. Biofertilizer
447 products must also go through field-testing as well as quality and safety checks before they
448 are issued with a generic name and released to the market. In Vietnam, several decrees were
449 passed in 2006 to set up regulatory laws including decrees requiring labelling of commercial
450 products and regulating the production and commercialization (including import and export)
451 of biofertilizers (Van Toan, 2016). The Law on Quality of Commercial Products published in
452 2008 also indirectly regulates the quality requirements and standards of biofertilizers (Van
453 Toan, 2016). However, even with these regulatory standards in place, improvements are
454 needed in the process of quality assurance and control frameworks. For instance, Van Toan
455 (2016) reported that most of the biofertilizers in Vietnam are not produced in sterile
456 conditions that results in low quality products. In Myanmar, the registration and quality
457 control of rhizobia inoculants produced by the DAR (sole source of inoculants in Myanmar)
458 are performed in accordance with the Fertilizer Control Order of 1985. A quality assurance
459 system is also in place to assess inoculant quality throughout production (Than & San, 2006).
460 The quality control program in Thailand is not mandatory and mainly targets rhizobia
461 products. Tests are performed by independent laboratories on a voluntary basis, following a
462 relative standard number of rhizobia cells per seed of about 10^5 to 10^6 cells seed⁻¹ (Herridge,
463 2008; Herrmann & Lesueur, 2013). The process of regulation, registration and quality control
464 of biofertilizers has not been put in place by the government of Cambodia. So far, there is
465 only detailed provisions published as the Law on The Management of Pesticides and
466 Biofertilizers. A similar situation has also been reported in Lao PDR, where no information
467 was found on the quality control systems put in place for development and production on
468 biofertilizers.

469

470 **6. Conclusion and Recommendations**

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

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

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

500 Biofertilizer demand and production in China are by far the highest of the GMR countries.
501 However, there is still room for product improvement and market expansion, considering the
502 vast agricultural land area, variety of crops and environmental conditions (soil types, climate
503 etc.). The number of biofertilizers produced and marketed in China has tripled over the past
504 two decades. There is, however, limited diversity in the microbial composition, with more
505 than 90% of the biofertilizers mainly containing a mix of *Bacillus* strains. Surprisingly, only
506 1% of registered products contain rhizobia strain(s) and there is a great need to promote the
507 use of rhizobia inoculants and BNF in the Chinese legume-based cropping systems.

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

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

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

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

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

551

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556

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