Écosystème et processus d'innovation pour les intrants biologiques à base de micro-organismes au Cambodge

Ecosystem and innovation process for bio-inputs based on micro-organisms in Cambodia

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RÉSUMÉ.
Cet article analyse l'émergence et les dynamiques d'innovation des bio-intrants à base de micro-organismes au Cambodge, dans un contexte marqué par une intensification agricole forte et une dépendance croissante aux intrants chimiques. Il mobilise un cadre d'analyse du système d'innovation par une revue de littérature, l'étude de deux cas pionniers, 48 entretiens semi directifs et trois ateliers participatifs pour examiner les trajectoires historiques, les acteurs, les verrous et les leviers du développement de ces bio intrants. Les résultats montrent que l'innovation reste limitée par des contraintes techniques (efficacité perçue faible, qualité variable, manque de ressources locales, infrastructures insuffisantes), institutionnelles (absence de politique de soutien, réglementation), économiques (marchés étroits, coûts élevés) et sociales (faible demande, pratiques orientées vers les intrants chimiques). Cette combinaison forme un cercle vicieux freinant l'essor des bio intrants. Toutefois, les initiatives locales – coopératives agricoles, ONG, chercheurs – révèlent un écosystème émergent autour de modèles de bio usines communautaires et de démarches participatives. Les ateliers prospectifs documentent des trajectoires de développement pour deux biofertilisants (compost/bokashi et EM). Ils soulignent l'importance du renforcement des capacités, de l'amélioration de la qualité, de la certification, de la mise en réseau et du soutien public

ABSTRACT.
This article analyses the emergence and dynamics of innovation in micro-organism-based bio-inputs in Cambodia, in a context marked by intense agricultural intensification and growing dependence on chemical inputs. It uses a framework for analysing the innovation system through a review of the literature, the study of two pioneering cases, 48 semi-structured interviews and three participatory workshops to examine the historical trajectories, actors, barriers and levers of the development of these bio-inputs. The results show that innovation remains limited by technical constraints (perceived low efficiency, variable quality, lack of local resources, insufficient infrastructure), institutional constraints (lack of support policies, regulations), economic constraints (narrow markets, high costs) and social constraints (low demand, practices oriented towards chemical inputs). This combination forms a vicious circle that hinders the growth of bio-inputs. However, local initiatives – agricultural cooperatives, NGOs, researchers – reveal an emerging ecosystem around community bio-factory models and participatory approaches. Forward-looking workshops document development trajectories for two biofertilisers (compost/bokashi and EM). They highlight the importance of capacity building, quality improvement, certification, networking and public support.

KEYWORDS. Agricultural bio-inputs; Biological control; Biofertilizer; Innovation system; Agro-ecological transition; Cambodia

1. Introduction

Conventional agricultural intensification—through pollution from chemical inputs (pesticides, fertilisers, herbicides)—increases costs for the environment and public health [LAZ 25]. In response, global calls for agroecological transformation have identified bio-inputs (bio-fertilisers and bio-pesticides) as pivotal catalysts [COT 22, DAY 24, BAR 17, FLO 19, NGA 25, RAM 20]. Micro-organisms, for example, fix atmospheric nitrogen, solubilise soil minerals, and enhance nutrient absorption by plants [GOU 25, THA 17]. Investment in bio-inputs, such as in Latin America, underscores their potential [GOU 24].

In the context of South Asia, these perspectives are receiving increased attention and are being discussed in a number of regional consultation workshops. Since the 1990s, Cambodia has witnessed a rapid transition in its agricultural sector, marked by a shift from low-input to high-intensity systems, characterised by significant chemical inputs [FLO 19, BUR 21, FAO 25]. This transformation has been accompanied by mounting concerns regarding public health and ecosystem degradation, underscoring the need for critical analysis and policy intervention [SHA 17, TRI 23]. The aforementioned issues provide a rationale for the implementation of research endeavours into substitute solutions for pesticides that agroecology has the potential to provide [DAY 24, BIE 25]. A key focus of this deployment is the self-production of inputs, with a particular emphasis on local biomass resources and the functionalities of micro-organisms in the production of biofertilisers or biostimulants. There is a paucity of knowledge surrounding the deployment of these innovations within the Cambodian context [ASS 24a, ASS 24b].

The present article aims to analyse how the processes of experimenting with micro-organism-based biofertilisers structure a technological trajectory of productive investment. In addition, it will discuss how this can support the acceleration of the agro-ecological transition in the context of Cambodia. We have therefore elected to contextualise our research within the framework of rice production in Cambodia. Rice is the food production that polarises and concentrates the transformative challenges of agroecology in terms of cultivated area, quantities of chemical pesticides used and populations impacted.

2. Conceptual and methodological frameworks

This study uses the agricultural innovation systems framework [TOU 15] to analyse how systemic technologies—such as micro-organism-based bio-inputs—structure innovation ecosystems [LAP 25, MAL 09]. Such ecosystems foster synergies among actors, synchronising research, entrepreneurship, and public policy to implement novel technologies in production systems.

The utilisation of an analytical framework, comprising a range of tools and evaluation approaches [BLU 24], was employed in the study of these ecosystems and the innovation processes documented. Two analytical tools were used: (1) Historical timelines to trace the emergence and use of bio-inputs in Cambodia [ADA 24]. (2) Functional mapping of the ecosystem, focusing on actors, relationships, and investments in micro-organism-based bio-input production.

The study focuses on two pioneering case studies in Cambodia, selected for their historical significance and representation of bio-input innovation trajectories with a focus on rice production (Table 1).

Types	Purposes	Main Actors	Location	Descriptions
- Compost **- Biopesticide**	- Self-production for organic market	- Farmers - Organic producer groups - Cheab Santipheap Satrey Klahan AC	- Kampong Chhnang (central Cambodia)	Driven by market demand for organic products, farmers were organized by cooperative and non-governmental organization (NGO) to produce horticulture and paddy. Local knowledge, local biomass and micro-organism were used.
- Bokashi	- Commercialization	- Tram Kak Union of cooperatives	Takeo province, (southern Cambodia)	With technical support from international NGO, local resource-based bokashi was scaling up and commercialized under operation of the union of cooperatives.

Table 1. Description of case studies

Cheab Santipheap Satrey Klahan Agricultural Cooperative (Kampong Chhnang)	Tram Kak Union of Agricultural Cooperatives (TrUAC, Takeo)
- Produces organic paddy rice for export market and safe vegetables for domestic (local school procurement), supported by Farmers and Nature Network (FNN) and local NGOs. - Organic rice is produced through Contract farming schemes with a private rice miller : Amru Co Ltd. Farmers use Coop organic fertilizer (ECOCERT-certified), compost, and green manure. - Net-houses and integrated pest management (IPM) tactics are employed for organic vegetable production, with support from local government and NGOs.	- Established in 2021, TrUAC operates four commercial enterprises: bokashi fertilizer, animal feed, rice seeds, and chicken production. - Bokashi production began in 2017 with an initial formula using Effective Micro-organisms (EM), later replaced by SBN (a microbial fertilizer made from fish, eggs, vegetables, fruits, and crude sugar) due to nutrient deficiencies. - Udom Sorya AC, a member cooperative, invested in machinery to produce bokashi pellets (25 kg bags) for easier application. - Bokashi is sold at 35,000 Riel/package (25 kg).

Table 2. Description of main actors in the case studies

In-depth interviews conducted with 48 key actors of bio-input innovation (farmers, NGO members, AC representatives, researchers, public institutions) (Table 3) using semi-structured questionnaires.

Type of Actors	Description of Institutions - 48 people	Nb of interviews
Farmers	Takeo; Kampong Chhnang -	10
Agricultural Cooperatives	TrUAC; Cheab Santepheap Neary Klahan AC; Krang Lavea AC; Preah Vihear Meanchey Union AC –	7
Enterprises	Cambodian Organic Agriculture Association; Ecocert; HUSK Ventures JUNLEN; Bayon Heritage; EM enterprise; SmartAgro –	7
Researchers	ECOLAND; CIRAD; IRD; CESAIN; Faculty of Engineering and Bio resources, RUA; Faculty of Agriculture and Food Processing, University of Battambang; Division of Research and Extension; Faculty of Agronomy, RUA – 7	10
Public institutes	MAFF/GDA; DALRM/GDA; Cambodian Agricultural Research and Development Institute (CARDI) –e	4
NGOs	GRET; FNN; AVSF; Uni4Coop; HEKS; GIZ; SSLA; DCA – 10 people	10

NOTE. Nb – Number ; AC – *Agricultural Cooperative*; AVSF – *Agronomes et Veterinaries Sans Frontieres*; CESAIN – *Center of Excellence on Sustainable Agriculture Intensification and Nutrition*; CIRAD – *Centre de Coopération Internationale en Recherche Agronomique pour le Développement*; DALRM – *Department of Agricultural Land Resource Management*; DCA – *Danchurch Aid in Cambodia*; ECOLAND – *Ecosystem Services and Land Use Research Center (RUA)*; FNN – *Farmers and Nature Network*; GDA – *General Directorate of Agriculture*; GRET – *Groupe de Recherche et d'Échanges Technologiques*; MAFF – *Ministry of Agriculture, Forestry and Fisheries*; RUA – *Royal University of Agriculture*; SSLA – *Sustainable Soil for Life Association*; TrUAC – *Tramkak Union of Agricultural Cooperatives.*

Table 3. *Key actor interviewed by using semi-structured questionnaire*

Participatory workshops were held to validate findings, reduce knowledge gaps and discuss future pathways for bio-input innovation (Table 4), gathering key actors and case study contributors. The workshop mobilized "Future Thinking for Transforming" [INA 08], specifically "Future Triangle" approach [INA 23] combined with a back-casting approach to discuss future aspirations, levers and lock-ins for bio-input innovation in Cambodia, focusing on 3 bio-inputs:

Workshop	Workshop Description	Date	Nb of Actors
Workshop 1	Validated narration of innovation process, preliminary findings for broadening knowledge and dissemination	8 Sep 2023	13 people
Workshop 2		15 Sep 2023	14 people
Workshop 3	Building a practical connection in the area of the bio-input innovation process and collaborative action/pathways in biofertilizer development.	17 Nov 2023	17 people (invited from workshop 1&2)

Table 4. *Description of series of workshops conducted participatorily with key actors*

3. Results

3.1. *Context of bio-input utilization in Cambodia*

Cambodia's law defines biological fertilizers as containing micro-organisms that fix nutrients or decompose organic materials to support crop growth [THA 17].

3.1.1. Historical transformation of bio-input in Cambodia

Post-Khmer Rouge (1975–1979), farmers relied on local inputs like compost and natural pesticides due to the unavailability of chemical alternatives [BUR 24]. By 1979, Cambodia's chemical-input use per hectare matched regional levels but remained below Thailand and Vietnam. Prior to 1998, the utilisation of fertilisers and pesticides in Cambodia was unregulated. However, the regulation of pesticides through the framework of the registry was initiated in 2002 [KEA 10]. The formulation and implementation of the National Strategic Development Plans (NSDP) placed significant emphasis on the promotion of agricultural intensification and the enhancement of exports. For instance, the policy on paddy production and rice export was initiated in 2010, followed by legislation on contract farming in 2011, regulations on pesticides and fertilisers in 2012, and the establishment of ACs in 2013.

Subsequent studies have indicated that Cambodian farmers have become reliant on chemical pesticides and fertilisers for the protection of their crops and the augmentation of yields [FLO 19, NGA 25]. Furthermore, analysis of FAOSTAT data reveals a substantial surge in the utilisation of chemical pesticides per unit of cropland in Cambodia during the period 2021-2023, surpassing levels observed in the majority of ASEAN nations (with the notable exceptions of Vietnam and Brunei) and worldwide [FAO 25].

Concurrent with the process of agricultural intensification, concerns regarding the sustainability of agricultural and food systems emerged in the early 2000s (Figure 1). Civil society has been playing an important role in mainstreaming safe inputs through agroecology initiatives and projects in Cambodia. It is evident that these entities have been instrumental in the promotion of a variety of approaches to sustainable development in agriculture and food systems. These approaches encompass the utilisation of sustainable practices and inputs, including organic production, compost/bokashi, EM and biopesticides. As early as 2006, the COrAA was already providing certification services to meet the domestic market demand for chemical-free and organic agricultural products from individual and/or producer groups in Cambodia. Moreover, the first documented experimentation with Trichoderma was conducted by a researcher from Cambodia in 2009 [KEA 10]. Subsequently, in 2011, the Ministry of Agriculture, Forestry and Fisheries endorsed the certification of Trichoderma for commercialisation [GIZ 24].

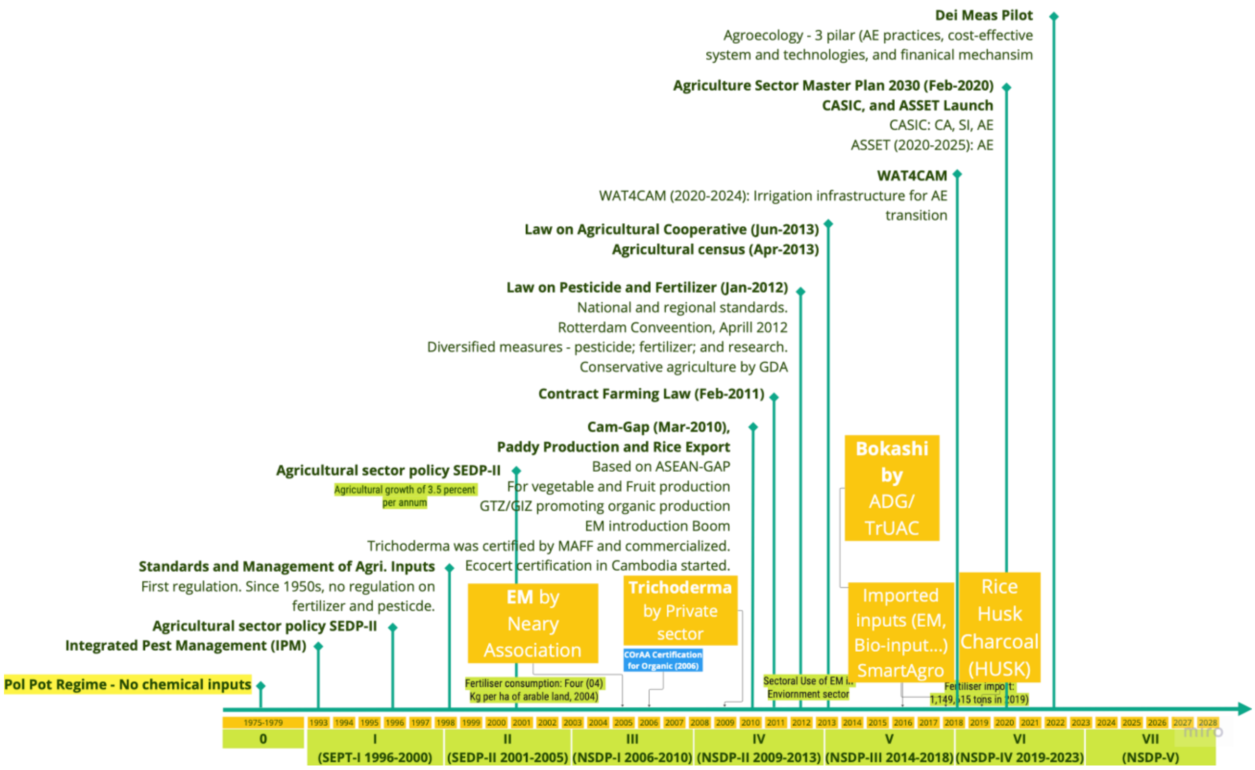

Figure 1. *Historical chronogram of bio-input innovations in Cambodia.*

Despite the absence of a specific policy to promote bio-input production and application, Cambodia has steadily engaged with ASEAN's efforts in the formulation of policy-related guidelines for agroecological transitions. For instance, in 2010, a new framework was developed and reinforced by the MAFF. This framework was based on the ASEAN-GAP framework, Cambodian Good Agricultural Practices (Cam-GAP) and Cam-Organic. These quality standards were designed to enhance the quality and safety of vegetable and fruit production, aligning with the ASEAN Guidelines on Soil and Nutrient Management [THA 19].

Recent initiatives have seen stakeholders coming together to promote enhanced coordination and support, with notable examples including the promotion of conservation agriculture and sustainable intensification in Cambodia. These efforts are directed towards the modernisation of agriculture and the transition to agroecological practices [MAF 24]. In 2004, the GDA of the MAFF initiated the adoption of innovative cropping systems and practices, grounded in the principles of Conservation Agriculture (CA). In 2020, the Cambodia Conservation Agriculture and Sustainable Intensification Consortium (CASIC) initiated a nationwide scale-up of these practices. Concurrently, the Agroecology and Safe Food System Transitions (ASSET) initiative was initiated with the objective of effecting a transformation in the food and agricultural systems of Southeast Asia, encompassing Cambodia, the Lao PDR and Vietnam, with a view to rendering them collectively more sustainable, safer and inclusive [ASS 20]. In 2024, the Association of Southeast Asian Nations (ASEAN) also released "Policy Guidelines on Agroecology Transitions in ASEAN", in which Cambodia was observed in the process of adoption [BIE 25].

3.1.2. *Various methods of bio-input production and application.*

This research is supported by a substantial body of empirical evidence, incorporating a range of literature, case studies and interviews. The study identified a variety of agricultural bio-inputs currently produced and utilised in the studied areas, including dry compost, dry animal manure, liquid compost, bio-slurry, bokashi, EM and vermicompost. The diversity of bio-inputs was contingent on the farming systems in question, be they rice-based, crop-based, or livestock-based. Horticultural systems were found to mobilise the widest range of bio-inputs. The majority of these were natural and/or micro-organism-based fertilisers and pesticides intended for use on vegetable and rice paddy crops, which represent the primary focus of most small-scale farmers. It is customary among farmers to report that natural and chemical fertilisers are used in combination for the purpose of higher yield of paddy rice production. The utilisation of natural fertilisers, such as dry compost and animal manure, is predominantly executed during the land preparation stage. Conversely, chemical fertilisers are employed during the growth stages of rice production.

As illustrated in Figure 2, farmers commonly used five bio-input products: dry compost, biopesticide, liquid compost, bokashi and EM. In contrast, bio-inputs were used by non-farmers as well. Researchers were found to prioritise the utilisation of compost and natural pesticides, Trichoderma, biogas plant waste, and other supplements, while enterprises appeared to engage in EM and supplements. In summary, it is evident that farmers lacked experience with the novel bio-inputs currently being explored by stakeholders.

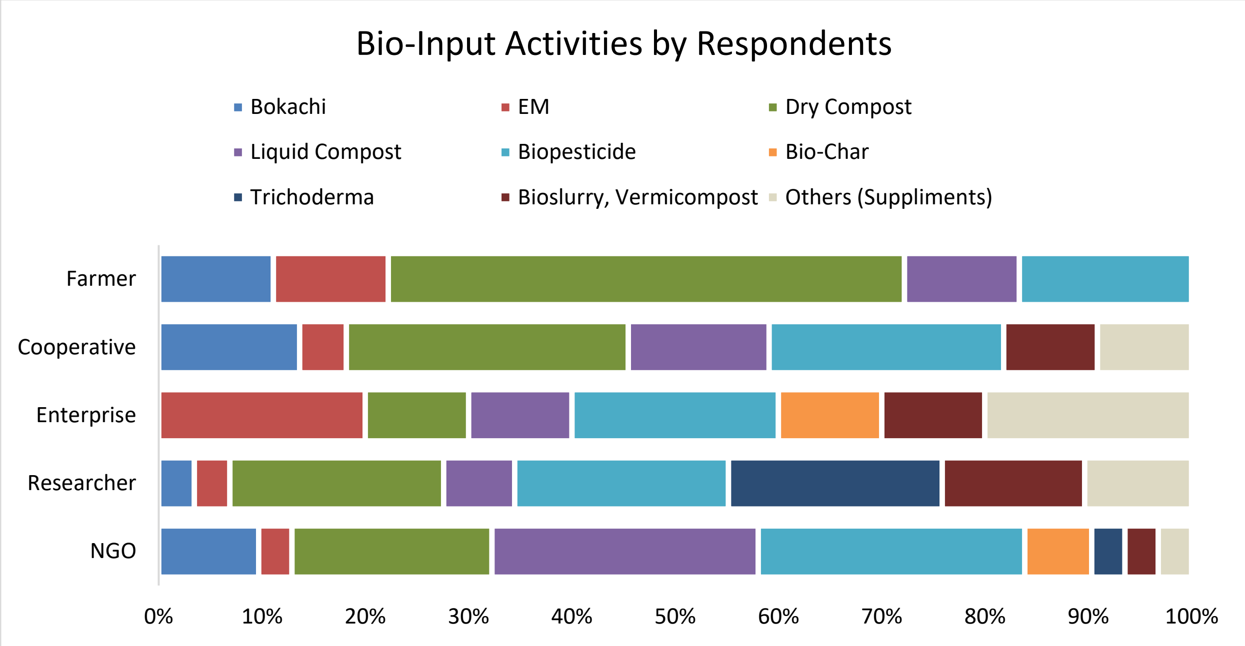

Figure 2. *Percent of respondents in engaging or bio-input activities (N=48)*

3.1.3. *Actors and functions in bio-input production and application*

Prior to the present study, there was no platform available for facilitating specifically bio-input actors to collectively share information and learn for the development of bio-input innovation. As demonstrated in Table 3, six distinct categories of actors were identified as being currently engaged in the active production and application of bio-inputs. The interaction between these key actors was characterised by dynamism and interconnectedness. Each actor contributed to the evolving system in advancing the production, application and regulation of agricultural bio-inputs.

Key Actor	Role	Challenges
Farmers	Use bio-inputs for self-consumption, safe production, and contract farming.	Limited knowledge, low perceived effectiveness, reliance on chemical inputs, and labor intensity.
Agricultural Cooperatives (ACs)	Facilitate production, training, and market access for bio-inputs.	Constrained by limited resources, fragmented governance, and weak coordination with stakeholders.
NGOs and Enterprises	Promote agroecological practices, provide training, and support value chains.	Lack of production capacity, reliance on external funding, and limited scalability.
Researchers	Develop and test new bio-input technologies (e.g., Trichoderma, EM, bio-slurry).	Disconnect between research and farmer adoption, limited lab infrastructure.
Public Institutions	Regulate and support bio-input policies, standards, and certification.	Ambiguous policies, limited biotechnology infrastructure, and slow policy implementation.

Table 5. *Description of the actors' characteristics in the system*

3.2. *Case Studies*

3.2.1. *Cheab Santipheap Satrey Klahan Agricultural Cooperative: Market driven adoption of bio-inputs*

The cooperative produces organic paddy rice and vegetables for domestic and export markets, supported by FNN and local NGOs. Thirty percent (30%) of the producers in organic contract farming use Coop organic fertilizer—certified by ECOCERT—alongside compost and green manure while other use exclusively animal manure. 8 – 10 bags of 25 kg of organic fertilizer are generally use at an average of 8.5-9.0$ per bag.

Farmers reported a range of challenges in producing and applying bio-inputs. Concerns were raised regarding the amount of labour and time required for the identification and collection of raw production materials. In essence, farmers reported diverse formulations and raw materials utilised for bio-input production, contingent on their respective availability. The raw materials employed in this study included animal manure and plants that were characterised by a strong smell and taste, such as neem leaves or bark, herbs, banana trunk, chilli, lemon grass, ginger and others. These materials were mixed with water, soap, seasoning and crude palm sugar. The materials under discussion were locally and seasonally available, including but not limited to neem leaf, chilli, palm sugar and other crop waste. Local plants such as Azola and Chromolaena odorata were frequently utilised for the purpose of compost production or green manure, with the objective of enhancing soil quality. The aforementioned approach was also employed in the treatment of rice blast/bacterial leaf blight during the rice growth period. The utilisation of traditional knowledge and nature-based bio-inputs was a principal feature of the agricultural practices employed by farmers from previous generations.

However, some farmers expressed scepticism regarding their comparative effectiveness in relation to chemical options. Moreover, concerns were raised regarding the duration required to observe tangible outcomes and the necessity of combining them with mechanical pest control to maximise their efficacy. It is evident that the utilisation of bio-inputs was predominantly influenced by three factors: existing knowledge and practices, the cost-effectiveness of production, and market requirements.

Figure 3. *Bio-pesticide fermentation in plastic containers (left) and application (middle and right) in organic vegetable production*

3.2.2. *The commercialization of bokashi fertilizer by the Tram Kak Union of Agricultural Cooperatives*

In 2017, a bokashi sample produced by TrUAC was analysed, with the following composition being reported: nitrogen (N) 1.1%, phosphorus (P) 7.35%, and potassium (K) 0.68%. This finding indicates that the produce exhibited a deficiency in nutrients when compared with chemical fertilisers. Consequently, TrUAC was compelled to enhance the quality of its product. In view of the limited availability of local production materials, TrUAC modified the formula, principally employing SBN in place of EM. SBN is a microbial fertiliser that is commonly known and introduced as a mixture of fish, eggs, vegetables, fruits and crude sugar.

Furthermore, farmers articulated a demand for pellets, as their application (i.e. the act of throwing them across paddy fields) would be more straightforward. Udom Sorya AC invested in machinery for the purpose of transforming the bokashi into pellets, as illustrated in Figure 4. The production of pellets was an intricate process that encompassed several distinct stages. The product was subsequently transformed into a pellet and packaged in bags of 25kg, in accordance with the demand of producers.

Figure 4. *Production of bokashi at Udom Sorya AC.*

In the market, the added value of bokashi was considered as good. Its price was 35,000 Riel/package (25kg), TrUAC made a considerable margin, corresponding to 28.5% of its production cost. However, the price of bokashi was competitive compared to other organic and chemical fertilizers. Its price was high compared to local price of chicken manure, which was widely perceived by the local farmers as good nutrients for their crops.

Types of fertilizer vs its local price	Unit (kg/bag)	Local Price * (USD/unit)	Local Price (USD/kg)
TrUAC bokashi fertilizer (pellets, operated by AC)	25	$8.75	$0.35
TrUAC bokashi fertilizer (powder, operated by AC)	25	$8.25	$0.33
Chicken manure (pack mixed with rice straw)	25	$0.88	$0.04
Coops organic fertilizer (Local product, Enterprise, certified by ECOCERT)	25	$9.00	$0.36
Carbon Based Fertilizer (Enterprise)	20	$8.00	$0.40
Chemical fertilizer (Imported product)	50	$40.00	$0.80

NOTE. Local prices were collected during Dec 2023.

Table 6. *Unit price of bokashi and its competitive products on the local market*

The bokashi business of TrUAC continues to encounter substantial challenges pertaining to both supply and demand. According to TrUAC's BoD, farmers expressed scepticism regarding the effectiveness of bokashi, which resulted in a limited local demand. It was reported by farmers that natural and chemical fertilisers were used in combination for the purpose of paddy rice production. In addition, it was reported by the farmers that the quantity of bokashi required was twice as much as that of chemical fertilisers, in order to achieve a comparable result. It is important to note that a number of other factors might be implicated, including but not limited to restrictions on the availability of raw materials, limitations in the utilisation of facilities (machinery, storage, transportation), improved quality or nitrogen content, and restrictions on promotional activities. The case study also demonstrated that the implementation of bio-inputs on a small scale represented a difficult endeavour in ensuring competitiveness in this context.

3.3. *Characterization of bio-inputs in the agricultural sector based on survey results*

Stakeholders recognize bio-inputs' potential to reduce costs, improve soil quality, and increase returns [GOU 24, GOU 25]. Local biofactories (e.g., bokashi) could replace synthetic fertilizers, but income gains are uncertain due to yield declines and lack of premium pricing

At the farm level, farmers encountered three primary constraints in the production and application of bio-inputs. These constraints included limitations in technical knowledge, scarcity of local resources for production, and the comparative effectiveness of bio-inputs versus common, available chemical inputs (Figure 5).

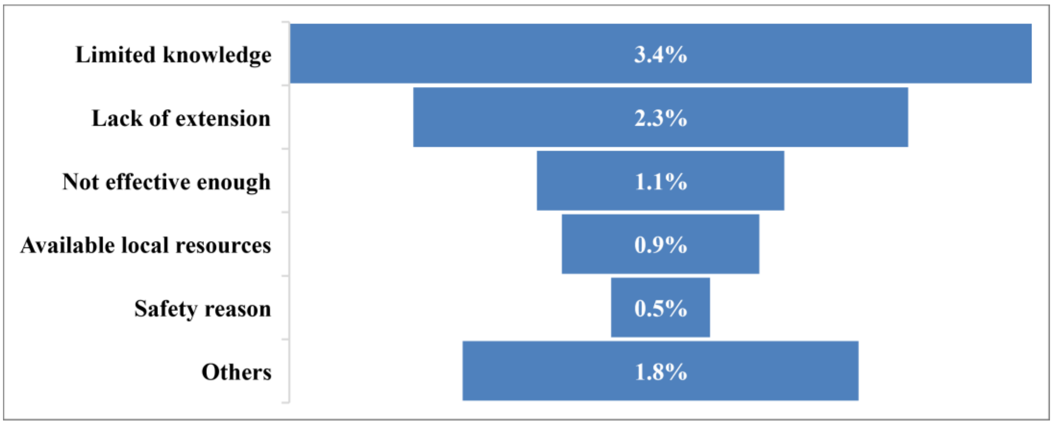

Figure 5. *Main locks that block the increase of the use of each bio-input at farm level (N = 48)*

It is evident that farmers have historically relied on bio-inputs under specific conditions, including self-consumption, safe-production, producer groups, and contract-farming. The scarcity of local material resources, the low perceived effectiveness of bio-input production and the challenging commercialisation at AC level in both case studies were significant factors hindering the expansion of bio-input production. The restricted demand gave rise to a corresponding limitation of production scale.

In a similar vein, AC representatives have identified a number of obstacles that must be overcome if biofertilizer is to be successfully commercialised. These include a paucity of raw materials that are either seasonally available or affordable, inadequate infrastructure for processing, storage and transportation, and marketing issues due to limited demand (current demand for horticulture and fruit crops). This limited demand can be attributed to the scepticism of farmers regarding the effectiveness of bokashi. The constraints on the commercialisation of bokashi fertiliser serve to emphasise the necessity for ACs to enhance their knowledge and business management skills. This suggests that the innovation system is characterised by weak formal coordination and fragmented governance.

Farmers exhibited a marked predilection for synthetic inputs, employing them to protect their crops from a range of pests. In the context of rapidly evolving agricultural development and modernisation, there is an increasing tendency to rely on chemical inputs [LAZ 25]. The case studies indicated the presence of an unmatched supply and demand issue.

In the absence of conducive policy and political determination to promote bio-inputs, the sector grapples with systemic challenges and is unable to achieve its full potential. The authorities responsible for the formulation of policy have expressed concerns regarding the risks associated with bio-inputs, given the limited scope of biotechnology in Cambodia. The hypothesis was formulated that the utilisation of micro-organism-based inputs would engender an as yet undefined degree of risk. The study revealed a paucity of advanced laboratories, with the majority being located in the non-agricultural sector. The aforementioned conditions gave rise to a considerable degree of complexity and costly certification processes, which had a deleterious effect on the willingness of producers to engage in bio-input manufacturing. It was recognised that micro-organisms were already being employed in a variety of sectors, including health, the supply of clean water, and the reduction of odours in animal manure. However, the researchers noted that standard protocols generally mandate a waiting period of 90-120 days prior to harvesting or local micro-organism in order to mitigate any potential risks.

3.4. *The proposition of pathways to biofertilizer development is hereby presented for consideration.*

The results of the participatory workshop revealed that the participants collectively expressed a shared desire to see an increased application of bio-inputs, with effective bio-input products that meet biotechnological standards, an improved value chain for bio-inputs through biofactories, and supportive public policies (Figure 6). However, it was also noted that concerns regarding the ineffectiveness and high cost of bio-inputs were identified as potential impediments to the successful coordination of innovation systems for biofactories in Cambodia.

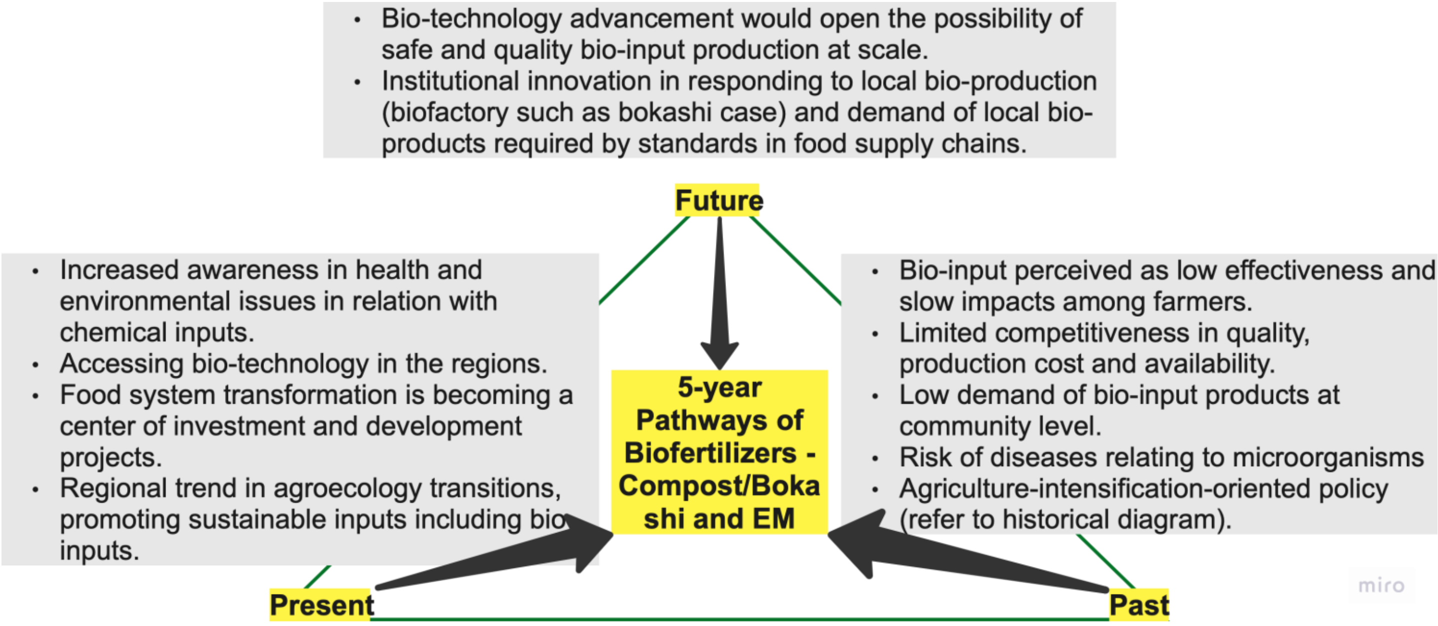

Figure 6. *Results of the Future Triangle of bio-input development are demonstrated.*

This finding also emphasised that the majority of participants expressed scepticism regarding the potential of bio-inputs at farm or landscape scales, citing various risks that had been articulated at that moment. The following elements were included:

• It is conceivable that the sector in question will be characterised by elevated costs, restricted accessibility, and a preponderance of large industries.

• The potential for inadequate policy support and a paucity of awareness is a matter of concern.

• The issue of increased importation of synthetic inputs has been identified as a potential risk factor, with the potential to limit the market for bio-inputs.

• The potential for adverse environmental consequences, including the risk of uncontrolled impact on soil and biodiversity, as well as the emergence of new diseases and environmental harm, is a salient concern.

The development of two biofertiliser products, namely compost/bokashi and EM, was achieved through the utilisation of participatory methodologies. In both cases, the pathways emphasised capacity building and co-creation, quality improvement, and commercialisation of the products. With regard to EM, participants emphasised the pivotal function of government certification in facilitating the augmentation of production and commercialisation (Figure 7). The network encompassed a variety of activities related to the production and sale of biofertiliser products. These products were disseminated through technical training, value chain development, and the marketing of bio-inputs.

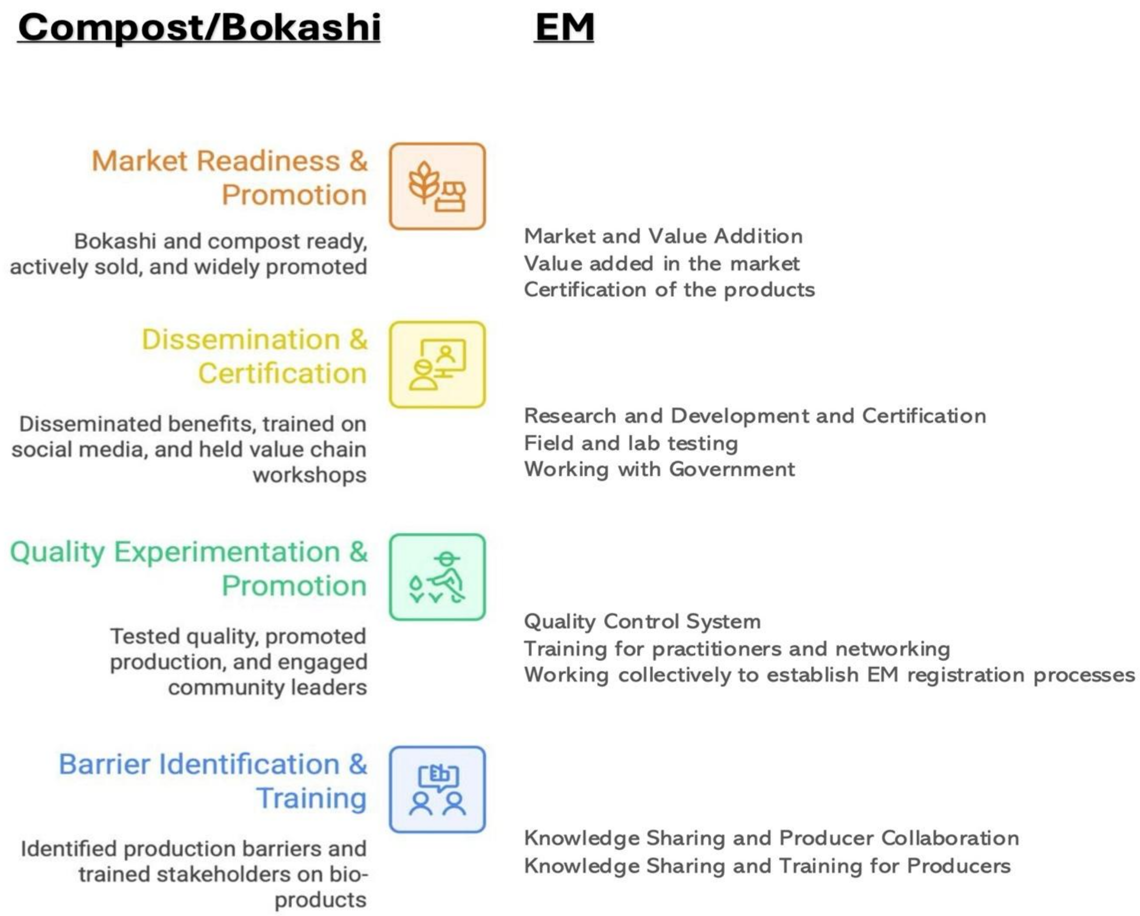

Figure 7. *Potential pathways for biofertilizer products over the course of the next five years.*

3.4.1. *Pathways of compost/bokashi*

As illustrated in Figure 7, the five-year pathway for compost and bokashi was established by the key actors in the biofertiliser sector during the workshops. In 2024, the focal point of the study was the identification of barriers encountered during the production and application of bio-products among the relevant stakeholders. Evidently, communication and training initiatives were accorded a high level of priority. By 2025, research efforts were to be focused on enhancing product quality and identifying optimal production methodologies. The promotional endeavours encompassed a series of initiatives, including meetings, field testing, and engagement with community leaders. In 2026, the emphasis would shift to the dissemination of the benefits of bio-products through workshops, training sessions, and certification processes. The exploration of marketing strategies, encompassing the utilisation of social media, is underway. By the year 2027, the emphasis should be directed towards the active selling and promotion of bio-products within the market. A number of efforts have been made to address this issue, including the dissemination of relevant documentation, an increase in production levels, the promotion of the initiative, and the enhancement of networking among the relevant stakeholders.

The importance of networking in facilitating the compost/bokashi pathway was identified. The establishment of a robust network of engagement in the commercialisation of bokashi products is imperative. The network encompassed a variety of activities related to the production and sale of products across the value chain and marketing. The implementation of a comprehensive marketing and branding strategy for bokashi products is imperative, with particular emphasis on the utilisation of farmer-level marketing initiatives. This will in turn prompt the supplier to increase production. In this particular context, networking is likely to be advantageous. The utilisation of social media for the purpose of facilitating social communication has been identified as a potential strategy to enhance the promotion and demand of bokashi. In order to enhance our comprehension of the technical intricacies and challenges inherent in these solutions, it would have been advantageous to engage in participatory research. A variety of training programmes are available, encompassing technical and communication modules that focus on the advantages of utilising compost or bokashi.

3.4.2. *Pathway of Effective Microorganisms (EM)*

The workshops placed particular emphasis on the collection and consolidation of EM producers, as well as the formulation of a precise and pragmatic road map for the standard, with the objective of facilitating its practical implementation (Figure 7). The ingredients to be used were to be defined for the effective standard. It was imperative that we engage with research and gain access to laboratory analysis. Furthermore, it is imperative to possess the capacity to collaborate with proficient government personnel in the domains of capacity building and certification processes, drawing upon the extant experience of other nations. Subsequently, the onus falls upon EM producers to assume responsibility for the maintenance of internal control systems through the implementation of in-house laboratory testing procedures. The overarching objective of this undertaking is to ensure the consistent fulfilment of quality standards. The acquisition of certification has been demonstrated to facilitate the establishment of a robust brand name and the attainment of a fair market value. Certification of a Participatory Guaranteed System (PGS) has been demonstrated to be a practical approach for EM products.

Quality control measures encompass the establishment of demonstration farms, the conducting of production inspections, and the utilisation of research and laboratory resources for the purposes of improvement and certification. The importance of collaboration with government entities is emphasised in the context of the registration of EM processes and the provision of training to officials in other countries. The certification process incorporates both external laboratory analysis and internal testing, thereby enhancing the value of EM products in the market.

4. Discussion

Micro-organism-based biofertilizers represent a nascent technological trajectory that could accelerate Cambodia’s agroecological transition. Workshop results highlight the importance of self-production and commercialization in reorganizing input markets**.** While local knowledge and resources exist, coordination remains limited, focusing primarily on horticulture

Despite the limited scale of the supply of these biofertilizers during the course of this study, there is nevertheless the potential for further development as biofactories for the benefit of smallholder farmers [GOU 24]. As was outlined in the discussions amongst the key actors, the quality of bio-fertilizers is to be improved and promoted through a participatory process.

However, within this experimental phase of technological development, the process innovation can be characterised as nascent in terms of its capacity to innovate, viability and sustainability. It is imperative that the necessary conditions for further experimentation with scaled bio-input products are established. This encompasses the following elements: learning processes in local biofactories (knowledge and governance at a cooperative level), coordination of actors, and public investment. The findings highlighted the technological trajectory's level of maturity. These enabling environments were interconnected, as illustrated in Figure 8. The study demonstrated that a combination of factors, including ambiguous policies, constrained production resources, elevated costs, circumscribed biotechnology research, diminutive markets with elevated prices and the perceived ineffectiveness of agricultural bio-inputs, engenders a cycle that perpetuates agricultural challenges and hinders the development of bio-inputs. It is evident that the limited production of micro-organisms and biomass, in conjunction with the utilisation of substandard bio-inputs, has exerted a simultaneous influence on both supply and demand.

This phenomenon has culminated in the absence of substantial economic incentives and a paucity of compelling evidence to substantiate policy directives that prioritise bio-input innovation in the context of agroecological transitions.

The supply of labour and resources was subject to restrictions that were influenced by a number of factors. Among these factors were migration flows, the availability of raw materials, and know-how, as well as competing activities. Conversely, market demand for bio-inputs was influenced by the availability of alternative products, particularly chemical ones, which offered higher yields and were commonly acknowledged among actors. It is evident that the perception of low effectiveness had a detrimental effect on local demand, which in turn had an impact on the scale of production. This vicious cycle is indicative of a misalignment of critical elements within the innovation system, specifically with regard to the biofactories model, coordination and public investment. The scaling up of bio-input production and application necessitates the disruption of this detrimental cycle, with all primary stakeholders having substantial roles to play in the technical, institutional, social, and political dimensions [BAR 17, GOU 24].

As illustrated in Figure 8, a comprehensive overview is provided of the technical, institutional, social and political contributions of the various key actors in disrupting the detrimental cycle of underdeveloped bio-input application.

It has been posited that the construction of infrastructure for the purpose of biotechnology has the potential to enhance the quality and effectiveness of bio-inputs, whilst concomitantly reducing cost, as has been identified by key actors. This finding suggests the necessity for the establishment of institutional support mechanisms and the coordination of innovation systems in terms of technical knowledge and extension among farmers and communities. The objective of this coordination is to enhance the effectiveness of the innovation system, ensure the maintenance of quality standards, and reduce management costs of fertility. The expansion of bio-input applications necessitates a comprehensive public support framework, encompassing modernised regulations, research and development (R&D) support, tax incentives, and the establishment of innovation networks [GOU 24]. Furthermore, in order to circumvent the issues of contamination and biological risk, it would be advisable for regulations on the labelling of bio-input products to adopt the ASEAN guidelines [THA 17, BIE 25, BAT 14], providing a minimum of instructions and information concerning contact details, storage, handling and shelf life. However, it was widely acknowledged that these measures were critical for this developing country, given its limited access to biotechnology and agricultural laboratories. It has been posited that it would require a considerable time period for public policy to assume an active role in bio-input innovation in Cambodia. Cambodia's current strategic focus on food security, price stability and intensification is the underlying factor. It is evident that public institutions, most notably the Ministry of Agriculture, Forestry and Fisheries (MAFF) and its associated departments, including the Department of Agricultural Legislation, the Department of Crop Protection, Sanitation and Phytosanitary, in conjunction with academic institutions, are assuming pivotal roles in the coordination of the innovation system.

As illustrated in Figure 8, a further pivotal power dynamic in the relationship under consideration is the alignment of the institutional actors within the prevailing agroecology network. This alignment should extend to incentive mechanisms, institutional factors, technical knowledge and markets, as well as adapted bio-based alternative technologies [FLO 21]. This may necessitate non-linear coordination processes across multiple dimensions when pursuing the aforementioned biofertiliser pathway agenda. As indicated by an extant study, the establishment of robust national networks that are endorsed by global networks is imperative [GIL 15]. It is therefore recommended that existing active networks, such as the CASIC and ALiSEA platforms, be utilised in order to facilitate the bio-input transition. ALiSEA is a regional platform that facilitates the exchange of expertise among local and regional stakeholders in the field of agroecology, with the objective of producing evidence-based studies. CASIC, meanwhile, is a broad network of organisations engaged in the promotion of conservative agriculture and sustainable intensification in Cambodia.

From a social perspective, the implementation of a reasonable price premium on agroecology products has the potential to indirectly incentivise food system actors to engage in agroecology production, thereby opening up the market for bio-inputs. The establishment of a business model would serve to facilitate the connection between the demand and supply of bio-input products in an AE food system market. It is imperative to recognise the significance of ACs and their unions in optimising the coordination of bio-inputs' demand and supply [GOU 24]. Non-governmental organisations (NGOs) have the potential to contribute to the interruption of the chain of risk by facilitating and enhancing the capacity of relevant stakeholders to make bio-inputs accessible and sustainable. This can be achieved through capacity building, awareness raising, and livelihood improvement. The private sector is poised to play a pivotal role in fostering the market for bio-inputs and bio-input-based agricultural products. This potential is anchored in the utilisation of diverse business models and the undertaking of rigorous research and development initiatives. These endeavours are poised to scale both technically and economically, thereby ensuring the market's optimal development.

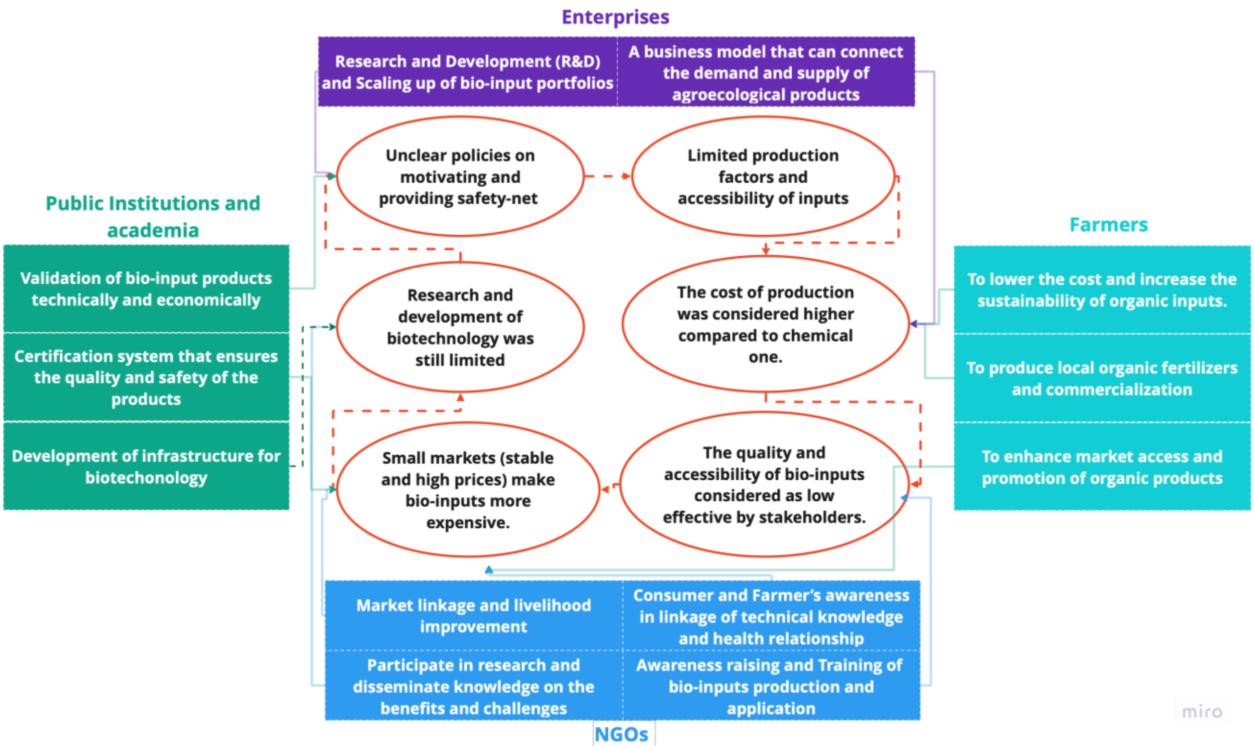

Figure 8. *Bottlenecks on demand and supply side, creating a vicious cycle of under innovation of bio-inputs*

From a political standpoint, the establishment of a public policy framework for an emerging innovation system has the potential to facilitate interaction among domestic actors [LUN 11]. Such a framework could encourage innovation in areas such as on-farm or community-based biofactories, while simultaneously raising consumer and farmer awareness. One potential solution to this issue is the establishment of on-farm and community-based bio-factories. The establishment of biofactories in Latin America has given rise to a range of novel prospects and innovative models [GOU 24]. The commercialisation of bokashi by the union of ACs serves as a prime example of the biofactory model for the production and access to agricultural inputs. Existing infrastructure investment has the potential to facilitate the scaling up of bokashi or other bio-inputs, thereby achieving autonomy and enhanced capacity within the agricultural input supply chain. This, in turn, would result in reduced costs and more accessible community-based input delivery.

A concerted research initiative, encompassing NGOs, researchers and farmers, holds the potential to propel the advancement of bio-inputs and their dissemination. This collaborative endeavour will entail the identification of optimal practices that are aligned with the technical and socio-economic imperatives of smallholder farmers. Participatory research is imperative to enhance comprehension of the obstacles confronting farmers and to promote advancement in their technical expertise. Moreover, the provision of economic incentives is instrumental in facilitating the transition to agroecology in Cambodia. As demonstrated by the results of the individual pathways of each biofertilizer (Figure 8), there is a clear necessity for active and robust networking, engagement in participatory research, living labs, certification and the commercialisation of products. The innovative capacity-building and collaborative research approach known as the Farmer Field School (FFS) approach, recommended by ASEAN [ASS 24a], has been demonstrated to be well aligned with the pathways of biofertilizer development discussed during the aforementioned workshops. The establishment of networks among relevant stakeholders has been identified as a potentially beneficial measure that should be formally institutionalised in order to facilitate the transition. This would be achieved through the collaborative development of a bio-input innovation system that is responsive to the livelihoods of farmers and the specific characteristics of the local context [GOU 25, BUR 22]. For instance, social media is regarded by key actors as an effective tool for connecting users, industry, science and policymakers to improve the quality, promotion and demand for bio-inputs. The on-farm evaluation of diverse materials, including the living lab or participatory guarantee systems (PGS) model, has the potential to contribute to cost reduction and enhanced system efficiency [ASS 24a].

Conclusion

Cambodia's bio-input innovation system is nascent, facing technical, institutional, and economic challenges. Although actors are willing to collaborate, interaction remains limited, creating a vicious cycle that requires evidence-based solutions. It is evident that there are common development pathways for bokashi/compost and EM, centred on collaborative platforms. These pathways ensure investment in biotechnologies to improve the quality of biofertilisers through farmer participation in innovation processes. They also leverage external expertise in evidence-based practices and policy support, and raise awareness among producers and consumers to connect supply and demand for bio-input products.

The dissemination of bio-input applications is closely associated with the enhancement of collective initiatives in the domains of research and the development of bio-input products among farmers, agricultural cooperatives, the private sector, researchers, NGOs and the government. These collective initiatives function in the areas of production, application and commercialisation. It is evident that these human resources have exhibited a collective commitment to propelling the agenda for biofertilizer innovation forward.

In order to achieve the maximum potential of biofertilisers and to develop innovative bioinput systems in Cambodia, it is vital that the collaboration and engagement of the biofertiliser network established during this study is maintained moving forward. The findings of this study have the potential to provide comprehensive guidance and strategic frameworks for the expansion of bio-inputs in Cambodia across a range of agricultural production systems. This encompasses not only rice production but also high-value product chains, including pepper, cashew, and vegetable crops

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