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Innovations in Agricultural Bio-Inputs: Commercial Products Developed in Argentina and Brazil

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Abstract: Innovations in agricultural bio-inputs can lead to sustainable alternatives to replace synthetic fertilizers and pesticides. However, there is no clear understanding of what technologies can become available to farmers as commercial products, particularly in developing countries. This study summarizes the innovations used in commercial products in Argentina and Brazil based on the countries' official data and on in-depth surveys conducted with 14 bio-input private companies. The results reveal ongoing development efforts to improve traditional products, such as inoculants that help plants fix nitrogen. There is also progress in mastering the formulation of new bio-inputs, such as bio-fertilizers that promote plant growth and bio-pesticides for pest control. Lastly, the next generation of bio-inputs composed of phytovaccines promises to help prepare plants' immune systems against the attack of pathogenic fungi and bacteria, while bio-herbicides can potentially reduce the use of synthetic herbicides to prepare fields for harvest. Domestic companies based in Argentina and Brazil play an important role in these innovations that can underpin bio-economy growth in developing countries.

Keywords: bio-fertilizer; bio-pesticide; phytovaccine; bio-herbicide; bio-economy; horizon scanning

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1. Introduction

Decreasing the use of synthetic agricultural inputs is a target shared by countries worldwide due to the negative impacts agrochemicals have on human health and the environment [1,2]. One of the main potential alternatives to agrochemicals is the use of bio-inputs whenever innovations provide solutions to supersede synthetic fertilizers, pesticides, and herbicides [3]. Agricultural bio-inputs are biological products developed from enzymes, extracts (from plants or microorganisms), microorganisms, macro-organisms (invertebrates), and secondary metabolites, which are intended for biological control, nutrition, and abiotic and biotic stress relief [4].

There is a growing market demand for agricultural bio-inputs, leading to important technological developments in this field. The global market for bio-pesticides was estimated at US $6.51 billion in 2022, with an estimated growth of 15.7% by 2029 [5]. The market for bio-fertilizers in 2022 represented US $2.02 billion, with an estimated growth of 12.1% by 2029, while the market for bio-stimulants in 2022 represented US $3.14 billion, with an estimated growth of 11.4% by 2029 [5].

Innovations range from improving the efficacy of existing bio-inputs such as inoculants, bio-fertilizers, and bio-pesticides [6–9] to developing new products based on modern technologies such as nanotechnology and molecular biology [10,11]. There are also efforts to combine different microorganisms into single products [12–14] that solubilize nutrients available in the soil and help plants resist pests and drought [15,16]. Industrial

processes such as bioreaction and lyophilization are also applied to prepare long-lasting and easy-to-apply bio-products [17,18].

After long processes of product development in public research centers and private companies, bio-inputs are becoming largely available to farmers in the marketplace. Inoculants were the first generation of bio-inputs to have a large-scale market, particularly for soybeans in the 1990s [6]. After 2015, a new generation of commercial products such as biological fertilizers and biological fungicides became available on the market, which resulted in the current growth in the bio-inputs sector [1]. Scientists expect that the next generation of bio-inputs will result from the growing market demand for bio-herbicides [19] and from developments in the field of biotechnology [11]. This recent market growth for large-scale crops took place alongside the steadily growing demand for peri-urban and organic areas, where synthetic inputs are not allowed [3].

Innovation in agricultural bio-inputs represents an opportunity for sustainable development in countries like Argentina and Brazil, which have a large demand for agricultural inputs [20,21]. Both countries have agricultural-related industries, support from public innovation centers, and dedicated policies promoting the sector of bio-inputs [22–24]. Strategic investments in this sector may also benefit from the growing market for bio-economy-related products [25].

However, despite the potential for innovation in agricultural bio-inputs and the intensive research by the public and private sectors reported by the scientific community, there is no clear understanding of what innovations are now available in the market or can potentially make it to the market in the coming years and what solutions they are expected to deliver [26]. We lack information from a horizon scanning approach to what is happening at the end of the product development pipeline, where products are either being developed and registered for commercial use or are becoming available in the marketplace [17,27].

This study aims to characterize the state-of-the-art in commercial agricultural bio-input development that can lead developing countries to play an important global role in sustainable agriculture. Specifically, we aim to:

- Summarize the innovations registered by governmental agencies for commercial use in Argentina and Brazil;
- Characterize the commercial products made available in the market or under development by private companies;
- Analyze the main market-related innovative pathways based on the products' and companies' characteristics.

2. Theoretical Framework

While the potential uses of microorganisms for agricultural purposes are well covered by the scientific literature [6,13], there are fewer studies on market dynamics, particularly on the innovations that are being made available in the market [21]. The existing literature on commercial agricultural bio-inputs highlights the importance of biotechnology to foster sustainable agriculture [28,29], its potential for bio-economy [25], as well as its limitations [30]. However, the academic literature still lacks a clear understanding of the existing innovations as a means to assess how the bio-inputs sector can eventually underpin bio-economy growth in developing countries.

The rising global demand for agricultural products presents opportunities for investments in innovative agro-industrial sectors in developing countries [31]. Innovation is a new or improved product or process (or a combination thereof) that differs significantly from the previous products or processes and that has been made available to potential users [32]. In other words, innovation can be defined as an invention that becomes a product available to consumers in the marketplace.

Developing countries often lack investments by industrial sectors for product development [33]. However, this is not the case for the sector of bio-input, which receives investments from both private companies (including startups) and public research centers [34].

Cooperation for innovation between private companies, universities, and research centers occurs moderately with domestic high-tech companies in developing countries [35,36].

Public research centers include mainly the Instituto Nacional de Tecnología Agropecuaria (INTA) in Argentina and the Empresa Brasileira de Pesquisa Agropecuária (Embrapa) in Brazil, but there are also universities and other important research centers in both countries [37]. These centers often develop new technologies that are then licensed to private companies that transform them into commercial products [23,24].

The development of a commercial bio-product begins with basic research to isolate and select the strains of beneficial microorganisms and laboratory tests to assess its efficacy. The next phases include trials in greenhouses to validate the product prototype in a controlled environment and field trials on farms that go along with the registration of the product for commercial use [17]. Once the product is registered, it can be made available on the market for farmers. The whole process of registering a product requires years of field testing with diverse crops and in distinct regions. The main types of agricultural bio-inputs available on the market are inoculants, bio-stimulators (bio-fertilizers), and products for plant therapeutics (bio-pesticides) [24]. Industrial agricultural bio-inputs are a new and growing sector with potential solutions for sustainable agriculture, which is also the case for other sectors such as organic fertilizers that use agricultural residues [38,39].

3. Methods

This study is based on official data on commercial bio-inputs and their active ingredients that are registered in Argentina and Brazil and on interviews with private companies that invest in research to develop new bio-inputs in these countries. The official data provided a comprehensive overview of the main technologies (extracts from live organisms or micro- and macro-organisms) used in both countries based on the products registered by private and public companies by January 2023. The interviews added information on the private companies' new developments and perspectives for the future based on the products these companies were expecting to have on the market in the coming years.

For Argentina, we used official data published online by the Argentinean Servicio Nacional de Sanidad y Calidad Agroalimentaria (National Service for Agrifood Health and Quality—SENASA) that registers the agricultural products used in Argentina. The study is based on two databases, which are the registered fertilizers (Registro de Productos fertilizantes, enmiendas y otros) [40] and the registered pesticides (Registro nacional de terapéutica vegetal) [41]. From the list of registered fertilizers, all bio-fertilizers under the titles fertilizante biológico and enmienda biológica were selected. From the list of registered pesticides, all bio-pesticides based on fungi, bacteria, or viruses were selected. While the second database provides the list of active ingredients for each product, the same information is not available in the first list.

For Brazil, we used data published by the Ministry of Agriculture Livestock and Procurement (Ministério da Agricultura Pecuária e Abastecimento—MAPA). In the option "Produtos formulados" of the Agrofit website [42], we selected all the classes that were listed as biological, i.e., acaricide, biological agent, bactericide, fungicide, insecticide, and nematicide. These lists provided the names of the registered products, the active principles, and the companies that registered these products.

We contacted all the companies with products registered that had a website in Argentina and Brazil by e-mail and/or WhatsApp provided on their websites. From the 22 companies that replied to our contacts, we interviewed 14 domestic companies that have capital either from Argentinean or Brazilian groups and that have a strong product development component in their business model. Between October 2022 and March 2023, interviews were carried out with representatives of seven companies from Argentina and seven companies from Brazil (Table 1). While most of the companies are small and family-owned, the sample also included medium-to-large corporations such as Nova (owned by two families from Argentina and one US investor), Protergium (part of the Argentinean group Terragene), Rizobacter (part of the Argentinean group Bioceres, which is listed in

the NASDAQ), Biagro (part of the Brazilian holding GoExper that also owns Simbiose and Bioma), Biotrop (part of the Brazilian private equity firm Aqua Capital), and Vittia (a Brazilian group listed in the Brazilian stock market, B3).

Table 1. Interviewed companies and their webpages.

Headquarters	Company (and Business Group)	Webpage
Argentina	Ceres Demeter	https://ceresdemeter.com.ar/
	Fragaria	http://fragaria.com.ar/
	Microvidas	https://www.microvidas.com.ar/
	Nova	https://laboratorios-nova.com/web/
	Protergium (Terragene)	https://protergium.com/es/
	Rizobacter (Bioceres Crop Solutions Corp)	https://www.rizobacter.com.ar/
	Summabio	https://summabio.com.ar/
Brazil	Biagro (Go Exper holding—Biagro/Simbiose/Bioma)	https://www.biagro.com.br
	Biotrop/Total (Aqua Capital private equity) *	https://biotrop.com.br/
	Forbio (Forus Group—Forquímica)	https://for.bio/
	Krilltech	https://krilltech.com.br/
	Moara	https://moara.agr.br/
	Vital Force (products registered as Vital Brasil)	https://vitalforce.com.br/
	Vittia	https://vittia.com.br/

* By September 2023, after this study was finished, Biotrop was sold to the Belgian company Biobest. Websites accessed on 18 January 2023.

Interviews were conducted in person in nine of the cases, and there were five interviews conducted by online video calls. Five of the in-person interviews included a visit to the company's plant and lasted for around two hours, while the other interviews lasted for around one hour. The interviews were not recorded, and no personal information became available. The interviews covered the characteristics of the commercial products, their development process, and the products that were being registered or in the stage of field validation and are expected to be made available in the market in the coming years.

A horizon scanning approach was deployed to make a first evaluation of the new technologies. Horizon scanning is the first stage of the subject-wide synthesis of evidence since it involves listing all the known options for addressing a particular problem [43]. While a complete review of the evidence base would be preferable, the scale and duration of such reviews are often impractical [44].

A cluster analysis using Ward's method with Jaccard distances was conducted to determine the companies performing the main technological developments that can lead to innovative pathways in the field of bio-inputs. For this, we used 28 variables in the survey that represent the technologies adopted by the interviewed companies. All variables were binary, i.e., either the company had or did not have the specific technology in its portfolio. The technologies were coded by segments composed of inoculants, bio-fertilizers, bio-pesticides, phytovaccines, and other developments. The software INFOSTAT version 2011 (Universidad Nacional de Córdoba, Córdoba, Argentina) was used to perform the cluster analysis [45].

4. Results

4.1. Products Registered by Governmental Agencies

The official data revealed that by January 2023, Argentina had registered 824 inoculants or bio-fertilizers and 39 bio-pesticides registered for plant therapeutics (Figure 1).

Companies in Argentina reported that some products used as both bio-fertilizers and bio-pesticides are often registered as bio-fertilizers since registering bio-fertilizers is less time- and resource-consuming than registering bio-pesticides for plant therapeutics. However, in the case of bio-pesticides, the registration must be made as plant therapeutics. It can be the reason why Argentina has many more products registered as bio-fertilizers when compared with plant therapeutics (or bio-pesticides).

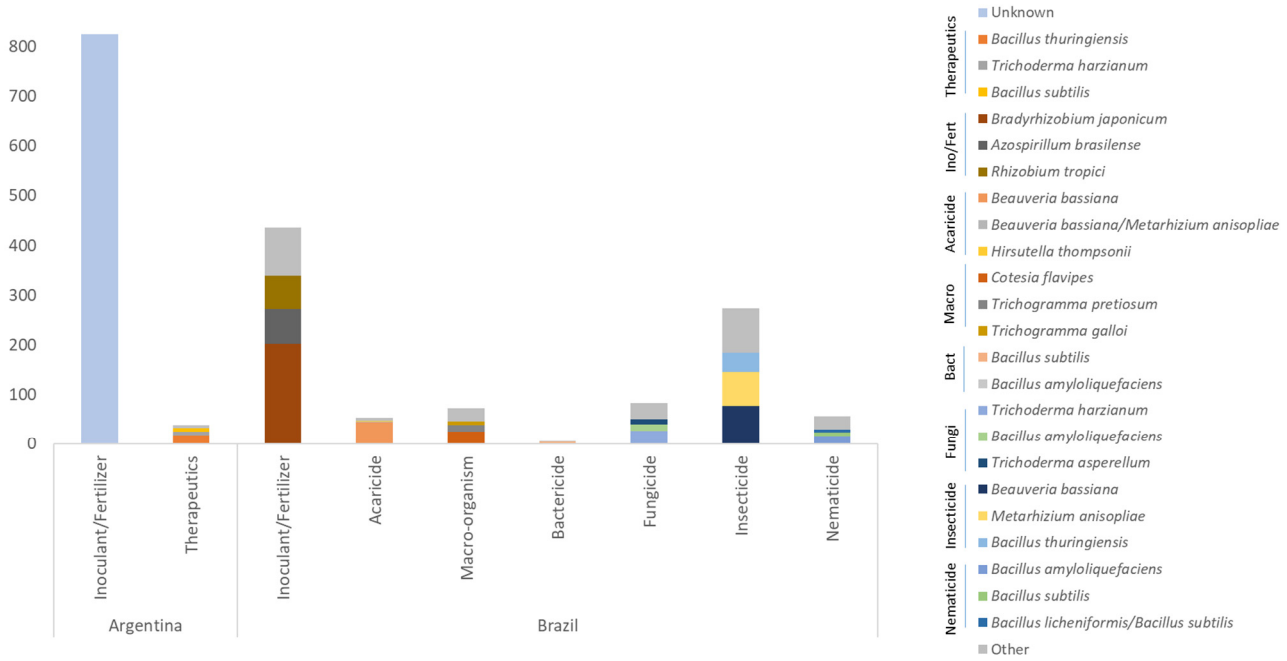

Figure 1. Total number of products and the most common technologies (microorganisms) registered in Argentina and Brazil by January 2023. Source: Adapted from SENASA for Argentina and MAPA for Brazil [41,42]. Note: While Argentina registers products either as bio-fertilizers or plant therapeutics, Brazil registers bio-pesticides (or plant therapeutics) as acaricide, biological agent, bactericide, fungicide, insecticide, and nematicide.

Most of the products for plant therapeutics in Argentina were based on the bacteria *Bacillus thuringiensis*, but there were also products based on the fungus *Trichoderma* and one virus. Whereas the active ingredients for inoculants and bio-fertilizers were not made available by SENASA, the interviewed companies mentioned that their products are mostly based on bacteria such as *Bradyrhizobium japonicum* for inoculants and *Bacillus subtilis* and *Pseudomonas fluorescens* for bio-fertilizers.

In Argentina, 123 companies had registered the 824 inoculants or bio-fertilizers, and 22 companies had registered the 39 products for plant therapeutics by January 2023, adding up to 129 companies in total since both types of products were registered by the same companies in some cases. The leading company in inoculants and bio-fertilizers is Rizobacter (part of the Argentinean Bioceres Crop Solution holding), while six other companies have three products each in plant therapeutics. As for the public companies, INTA registered one product for plant therapeutics, and YPF Sociedad Anonima registered two bio-fertilizers [41].

By January 2023, Brazil had 436 inoculants or bio-fertilizers and 546 bio-pesticides registered by the MAPA, half of which were registered as insecticides, but the list also included acaricides and other products (Figure 1). The vast majority of the acaricides were made of the fungus *Beauveria bassiana*, but there were also products based on other fungi and mites. Most of the agents for biological control were macro-organisms such as wasps of the genus *Cotesia* and *Trichogramma*, but there were also bugs and mites. The few bactericides were made of bacteria of the genus *Bacillus*, while the fungicides were made of fungi of the genus *Trichoderma* or bacteria of the genus *Bacillus*, either as isolated microorganisms or as pools of different organisms. Finally, bio-insecticides were mostly

made of the fungi *Beauveria bassiana* and *Metarhizium anisopliae*, and the nematicides were made of bacteria of the genus *Bacillus*.

Bio-pesticides (such as fungicides, insecticides, etc.) are registered in accordance with the Pesticides Law (lei 7802/89) in Brazil, but biological products can also be registered as inoculants or as phytosanitary products approved for use in organic agriculture. Since phytosanitary products approved for use in organic agriculture have low toxicity, their registration is faster than registration by the Pesticides Law.

In Brazil, 45 companies had registered the 436 inoculants and bio-fertilizers and 114 companies had registered the 546 bio-pesticides by January 2023, adding up to 137 companies with bio-inputs registered in Brazil since both types of products were registered by the same companies in some cases. The leading company in inoculants and bio-fertilizers was Biotrop/Total (Biotrop is the trade name of a company that is part of the Brazilian Aqua Capital private equity fund that registered products as Total). The leading private companies in bio-pesticides were Koppert (a Dutch company) for acaricides, Promip (a Brazilian company) for macro-organisms, Biotrop/Total for fungicides and nematicides, and Simbiose (part of the Brazilian GoExper holding) for insecticides. As for the public research centers, Embrapa registered 18 inoculants, and Embrapa and Ceplac registered one insecticide each [42].

4.2. Developments Reported by Companies

The interviews with companies revealed many commercial development fronts underway, including products that are available on the market and products that are still being developed or registered. These developments bring recent improvements in traditional products such as inoculants, efforts to master the formulation of pools of microorganisms in bio-fertilizers and bio-pesticides, and the ongoing development of new products such as phytovaccines and bio-herbicides (Figure 2).

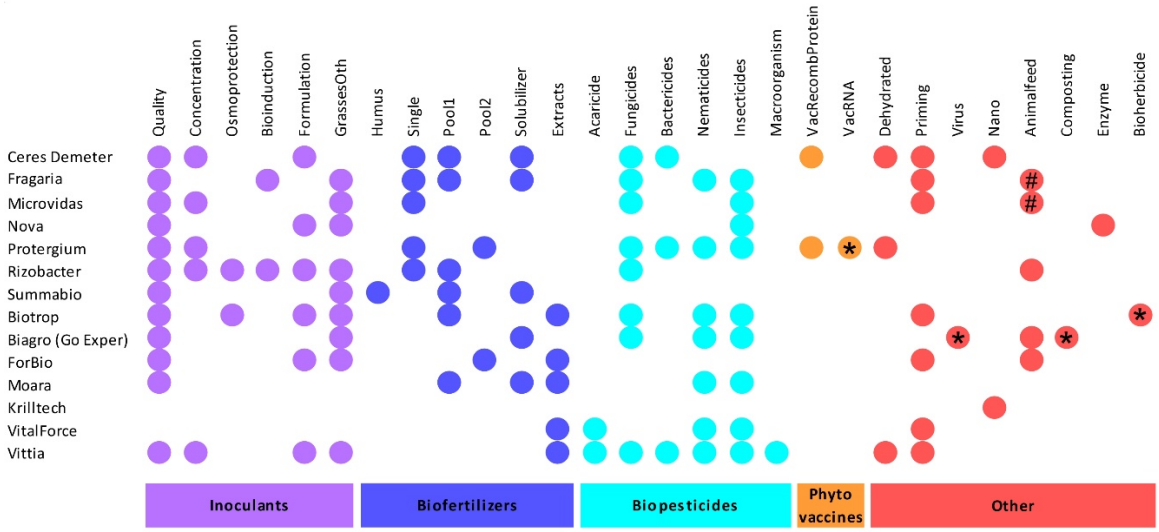

Figure 2. Number of cases of innovations in bio-inputs reported by the interviewed companies. Source: Interviews with companies' representatives. Note: Innovations listed in the figure are available in the market except for the cases where the products are still being developed (noted as *) or registered (noted as #).

4.2.1. More Efficient Inoculants

Large-scale commercial use of inoculants in Argentina and Brazil began with the bacteria *Bradyrhizobium japonicum* used in soybean seeds to improve the plants' capacity to fix nitrogen (Table 2). Over time, different technological developments were made available in the market, such as the selection of more efficient strains of bacteria, formulations in high concentrations, osmoprotection, use of bio-inductors to anticipate the exchange of signals between the root and the microorganisms, and improved formulations with better efficacy

(e.g., long-living bacteria, resistance to abiotic stress, and organisms with climate change mitigation effects). Additionally, inoculants were developed for cereals such as corn and wheat based on the bacteria *Azospirillun brasilense* and for other crops such as fruits and vegetables based on the bacteria *Rhizobium tropici* and others.

Table 2. Generations of technological developments in bio-products in Argentina and Brazil.

Generation	Uses (Most Common)	Characteristics	Active Ingredients (Most Common)	Main Technological Development
First	Inoculants to promote nitrogen-fixing by plants	Isolated conventional bacteria	*Bradyrhizobium japonicum*	Isolating, growing, and preventing contamination
Second	Bio-fertilizers for plant growth and nutrient solubilization	Non-conventional PGPR bacteria (isolated or in the pool)	*Bacillus subtilis* and *Pseudomonas fluorescens*	Keeping the stability and levels of different organisms over time
Third	Bio-pesticides for pest control	Pool of isolated, non-conventional bacteria, fungi, and viruses	Bacteria + fungus such as *Trichoderma harzianun*	Isolating spore-producing organisms and stabilizing the fungi
Fourth	Phytovaccines that activate plants' immune systems	Molecular biology to produce recombinant proteins, peptides, and ribonucleic acid (RNA)	Bio-elicitors made of pathogenic fungi or bacteria	Know-how in molecular biology and industrial processes

Source: Interviews with companies' representatives.

All but two interviewed companies have inoculants in their portfolio, and some are focused on developing more efficient inoculants given the size of their market. For example, the Argentinean Rizobacter is a global leader in inoculants for soybeans, and the company is also developing new products on the Rizoliq platform. Biagro (Go Exper) in Brazil also has important developments in inoculants, including Biagro N2 with *Azospirillum brasilense* for grasses and Biagro beans with *Rhizobium tropici* for beans. Almost all companies in Argentina use the *Bradyrhizobium japonicum* strain E109, isolated by the public agency INTA, and companies in Brazil also use strains isolated by different public agencies.

4.2.2. Bio-Fertilizers Made of a Pool of Organisms

Commercial bio-fertilizers began with liquid humus containing non-isolated microorganisms obtained from roundworms. The next generations had single-isolated bacteria, and the recent formulations focus on pools of different bacteria (Pool 1) or pools of bacteria and fungi (Pool 2) (Figure 2). The limited number of companies associated with Pool 2 is explained by the challenges of stabilizing mixes of different organisms, a technology that is still being mastered by companies. Developments already available on the market include the use of plant growth-promoting rhizobacteria (PGPR), such as *Bacillus* and other genera, to promote plant growth. Ongoing developments are related to trying out different organisms, assessing their efficacy, and reaching stable formulations of organism pools.

An important recent commercial development in this segment was the use of soil-nutrient-solubilizing bacteria such as *Pseudomonas fluorescens*. Further developments resulted in pools of other organisms, such as *Bacillus megaterium* and *Bacillus subtilis*, that resulted in the leading phosphorous (P) solubilizer product in the Brazilian market. Innovation centers and companies continue working with different pools of organisms to solubilize different nutrients, such as potassium (K) and others.

Bio-extracts are another area for the development of bio-fertilizers, which include extracts of algae, amino acids, and biopolymers produced by the cells of living organisms and used to protect seeds and bacteria in inoculants. The Argentinean Ceres Demeter is registering Biopol P1 as a mix of natural polymers and sugars for coating peanut seeds, capable of protecting the shell and increasing the adherence and survival of growth-promoting microorganisms on it, improving fluidity compared to untreated seeds. In Brazil, Biotrop has Bionatus (based on extracts of the algae *Ascophyllum nodosum*) positioned in

the market as a renewable biodegradable organo-mineral fertilizer; Forbio has Adiplus SojaFort NOD as a biopolymer to protect bacteria inoculated into soybean seeds; and Vital Force has Stimulus Root, which contains amino acids from algae.

All but two of the companies interviewed have bio-fertilizers in their portfolios, but some have a greater focus on bio-fertilizer development. For example, the Argentinean company Fragaria is now combining the bacteria *Azospirillum brasiliense* and *Pseudomonas rhodesiae* to prepare the fertilizer Acqua Duo, which is a PGPR bio-stimulator that solubilizes phosphorus. The Brazilian company Moara developed the product Bioprosolo using three species of *Bacillus* to solubilize P, stimulate root growth, and induce drought resistance. Go Exper is a leading company in P solubilization with a pool of *Bacillus megaterium* and *Bacillus subtilis*, developed in collaboration with Embrapa and registered as Biagro Energia by Biagro and BiomaPhos by Bioma.

4.2.3. Bio-Pesticide Formulations for Bio-Control

Commercial bio-control began with the use of some species of non-pathogenic fungi that control other species of pathogenic fungi. It then evolved to products combining different fungi and bacteria, resulting in products labeled on the market as bio-acaricides, bio-fungicides, bio-bactericides, bio-nematicides, and bio-insecticides. Ongoing developments are related to improving the long-term stability of the formulations, particularly those mixing bacteria and fungi. Such effort often implies having dedicated zones (or industrial plants) to work with microorganisms that produce spores, such as *Bacillus* and *Trichoderma*, and other zones to work with microorganisms that do not produce spores, as a means of preventing contamination by spores.

Developments in this sector also include isolating strains of new microorganisms to be used as bio-controls for different pathogenic organisms. For example, while the fungus *Beauveria bassiana* is well known by different companies, some companies invested in species of the genera *Metarhizium* (fungus) and *Streptomyces* (bacteria) to develop new fungicides. Formulations are also important to guarantee the quality of the product; while some companies use solid subtracts (such as rice), others multiply the microorganisms in liquid subtracts in bioreactors as a means of inducing the production of metabolites.

All but three interviewed companies have bio-pesticides in their portfolio, but with a distinct focus on fungicides, bactericides, nematicides, and insecticides (Figure 2). For example, in Argentina, Microvidas has the fungicide Trichovidas (*Trichoderma harzianum*) as its main commercial product, while Ceres Demeter is developing ISR Wheat and ISR Peanuts, both based on different strains of *Bacillus*, to control fungi, mainly *Fusarium* and *Sclerotinia*. In Brazil, Vital Force has BioBVB based on *Beauveria bassiana* registered as an insecticide but also with acaricide effects, and the insecticide BioScap Liq based on *Beauveria bassiana* and *Metarhizium anisopliae* as its leading commercial product. Biotrop has the fungicides Bombardeiro and Biomagno, the nematicide Furatrop, and the insecticides Biokato and Olimpo on the market.

Macro-organisms are also deployed for bio-control in commercial products used as parasitoids or predators of insects and other pests. For example, Vittia has the product GALLOI-VIT (*Trichogramma galloi*), which is a biological control agent used to destroy the eggs of *Diatraea saccharalis* in sugar cane plantations. Companies are also beginning to work with viruses, and Biagro mentioned that the Go Exper holding is developing the virus-based product VirControl.

4.2.4. Phytovaccines as Molecules for Specific Targets

Applied biotechnology has allowed the development of active principles through the use of recombinant proteins, peptides, or RNA interference that can be used as phytovaccines to prepare the plants' immune systems to resist the attack of pathogenic organisms such as fungi or bacteria. Recombinant proteins can promote efficient absorption of minerals and tolerance for stressful situations. The technique uses an isolated deoxyribonucleic acid (DNA) sequence from a pathogenic fungus or bacteria that is introduced in a bac-

teria or yeast that works as a factory to reproduce a target protein. Once the product is homogenized, the host bacteria are destroyed, and the resulting recombinant protein is used as an active ingredient for preparing bio-inputs. Similar biotechnology routes are used for peptides and ribonucleic acid (RNA), but the use of RNA interference requires encapsulating the molecule as a means of providing it with environmental stability. The resulting product is used as a bio-elicitor that activates the immune systems of the plants, playing the role of a phytovaccine.

The large-scale use of protein in pest control dates back to the application of *Bacillus thuringiensis* (BT) crystal protein to control lepidopterous larvae. Dating back to the 1920s, this innovation continued to be used as a commercial product even after the development of genetically modified BT corn. The phytovaccine differential is that it acts on the plant to prepare its immune system against potential pathogenic pests and does not act on the pests themselves.

Only two companies mentioned they were developing phytovaccines as bio-elicitors. Protergiun is registering two products as biological conditioners (one for soybeans and the other for cereals) based on molecular biology, whose active ingredient is a recombinant protein, and is also developing a product based on RNA interference. Ceres Demeter also mentioned investments in a metabolite of *Streptomyces* recombinant that can be used as priming, whose timely application increases the plants' capacity to resist stress. The only competitor in this segment in Argentina is Tropfen, which is marketing Tropbio Pro, a product that is made of the Harpin αβ protein extracted from the bacteria *Escherichia coli* using technology developed by a US company. This technology is not listed in Table 3 since it is dedicated to innovations conducted both in Argentina and Brazil.

Table 3. Examples of state-of-the-art technologies of the main types of bio-inputs that are either available in the market or are under development in Argentina and Brazil (name of the commercial product and description).

Use	Company	Developments in the Market	Ongoing Developments
Inoculants	Rizobacter	Rizoliq—*Bradyrhizobium* sp. in high concentration in the container and on the seed	Rizoliq Dakar—*Bradyrhizobium japonicum* and *Bradyrhizobium diazoefficiens* for better biological fixation in environments of water deficiency and high temperatures
	Biagro (Go Exper)	Biagro N2 with *Azospirillum brasilense* for grasses and Biagro Beans with *Rhizobium tropici* for beans	Liquid and peaty (turfoso) inoculants for 21 days of pre-inoculation
Bio-fertilizers	Fragaria	Acqua Duo—*Azospirillum brasiliense* and *Pseudomonas rhodesiae* as a PGPR and P solubilizer	Bio-fertilizers based on *Bacillus* since it grows faster than conventional bacteria and has both PGPR and therapeutic effects
	Moara	-	Bioprosolo (Registering)—Three species of *Bacillus* to solubilize P, stimulate root growth, and induce drought resistance
	Summabio	Summabalance and Summaroot (liquid humus + Isolated *Pseudomona* and *Bacillus* + micronutrients)	Include *Trichoderma* in the platform
Bio-pesticides	Microvidas	Trichovidas—*Trichoderma harzianum* as a bio-fungicide	Studying the potential of lyophilization for having solid instead of liquid products (focusing on *Trichoderma*)

Table 3. *Cont.*

Use	Company	Developments in the Market	Ongoing Developments
Bio-pesticides	Biotrop	Fungicides Bombardeiro and Biomagno, nematicide Furatrop, and insecticides Biokato and Olimpo	Solid bio-pesticides (Olimpo, the first commercial product)
	Vital Force	Insecticide BioScap Liq based on *Beauveria bassiana* and *Metarhizium anisopliae*	Bio-nematicides and plant resistance induction
Phytovaccines	Protergium	Phytovaccine based on recombinant proteins—Products of the molecular biology platform registered as two bio-conditioners, one for soybeans and the other for cereals	Phytovaccine based on RNA interference (developing)
	Ceres Demeter	-	Metabolite of *Streptomyces* recombinant
Other—Priming	Vittia	Priming—Bio-Immune has endospores that induce plant resistance	Gene silencing in specific microorganisms and investments to increase the portfolio of macro-organisms
Livestock feeding	Forbio	-	Inoculant Forsilo made of *Lactobacillus plantarum* to accelerate the anaerobic fermentation of silage to improve the quality of the feed offered to cows
Nano	Krilltech	Arbolina, which is based on organic carbon nanoparticles	Exploring possibilities to combine microorganisms and organic nanoparticles
Enzymes	Nova	Enzymes Xilanasa and Fitasa used to improve livestock digestion	Peptides from bacterial fermentation to be used as biofungicides

Source: Interviews with companies' representatives. Note: The companies and products listed in this table are examples of technological developments. There are other companies in each sector, and companies also have other products in addition to the ones mentioned in this table.

4.2.5. Other Ongoing Developments

Interviewed companies are investing in a variety of new technologies, ranging from new products to new industrial processes, as summarized below.

- Priming—Priming is the timely use of products to increase the plants' capacity to resist biotic stress, such as fungi attack, and abiotic stress, such as drought. Different types of bio-inputs used at the right moment can have priming effects. The Argentinean companies Protergium and Ceres Demeter mentioned developing products to be used for priming. In Brazil, Vittia mentioned that its commercial fungicide and bactericide, Bio-Immune, based on *Bacillus subtilis*, has endospores that induce plant resistance. They also mentioned working with gene silencing in specific microorganisms.
- Dehydrated products—Industrial processes such as lyophilization using low temperatures and sprays using heat are deployed to have solid/powder products (noted as wettable powder—WP) that reduce the costs of logistics. In Argentina, Fragaria uses lyophilization to prepare Biosilo, marketed under its own brand, and a probiotic produced for a third party. In Brazil, Biotrop uses lyophilization to prepare the insecticide Bioolimpo, sold as a powder-based product.
- Virus—Insect viruses are disease-causing organisms that reproduce within a host insect and can control a variety of insects that attack crops. Biagro mentioned that the Go Exper holding is developing the product VirControl based on viruses.
- Nanotechnology—Nanoparticles can be used as nanopesticides or nanofertilizers that enhance the capacity of plants to absorb nutrients. The Argentinean Ceres Demeter is developing a bio-input that includes microorganisms and organic nanoparticles, while

the Brazilian Krilltech already has on the market the product Arbolina, which is based on organic carbon nanoparticles that function as physiological promoters.

- Inoculants for livestock feeding—Bacteria can be used to improve the quality of livestock feeding. In Argentina, Fragaria has Biosilo on the market as an inoculant for silage made of lactic acid bacteria (*Lactobacillus plantarum*, *Pediococcus acidilactici*, and *Lactobacillus buchneri*) and cellulolytic enzymes, and Microvidas is developing products to be inoculated in cattle feed using bacteria of the genus *Pseudomonas*. The Brazilian Forbio is developing the product Forsilo made of *Lactobacillus plantarum* to accelerate the anaerobic fermentation of silage and improve the quality of the feed offered to cows.
- Composting—Bio-inputs can be used to accelerate the process of bio-composting. Biagro mentioned isolating an inoculant for composting.
- Enzymes—Enzymes are proteins that act as biological catalysts by accelerating chemical reactions. The Argentinean company Nova has an industrial plant dedicated to the production of enzymes, where they use different biological platforms to manufacture Xilanasa and Fitasa, which are enzymes used to improve digestion by monogastric livestock such as chickens and pigs (Table 3).
- Bio-herbicides—Bio-herbicides can reduce the use of chemical herbicides to prepare fields for mechanical harvest. Biotrop mentioned developing a bio-herbicide for broad leaf weed in Brazil.

4.3. Innovation Pathways

The description of the innovations in Section 4.2 revealed different efforts for technological development and levels of exclusivity in the types of commercial products, ranging from simpler technologies such as inoculants that are mastered by a large number of companies to new developments such as phytovaccines based on recombinant proteins that are being developed by a few companies. By crossing these two variables (technological developments and levels of exclusivity in the market), there are different pathways for technological development:

- Improving traditional products such as inoculants to compete in a large and consolidated market that has many competitors, small profit margins, but a large scale of sales. Some companies stand out in this sector, such as the Argentinean Rizobacter, which became a global leader in inoculants;
- Mastering new products such as bio-pesticides and bio-fertilizers to meet growing demand from more exclusive markets that have large profit margins but are still niche markets in some cases. For example, while nematicides used in soybean fields are mostly biological (since biological products are often more effective than chemical products to control nematodes), bio-insecticides are often used alongside chemical products to reduce the number of applications of chemical products. Targeting this market, the Brazilian company Vittia specialized itself in bio-pesticides based on micro- and macro-organisms.
- Developing innovations to conquer new and more exclusive technology-based markets by meeting existing demands for specific products. The Argentinean Protergium stands out in the segment of phytovaccines with two products based on recombinant proteins that are being registered.

Figure 3 also reveals that, considering the types of innovations developed by the interviewed companies, Argentinean companies tend to be grouped in the first cluster of companies (blue lines), while Brazilian companies tend to be grouped in a second cluster (green lines). Since the countries have different natural conditions (Brazil is a tropical country while Argentina ranges from subtropical in the north to polar in the south), this may reveal that the domestic companies focus their R&D on local conditions.

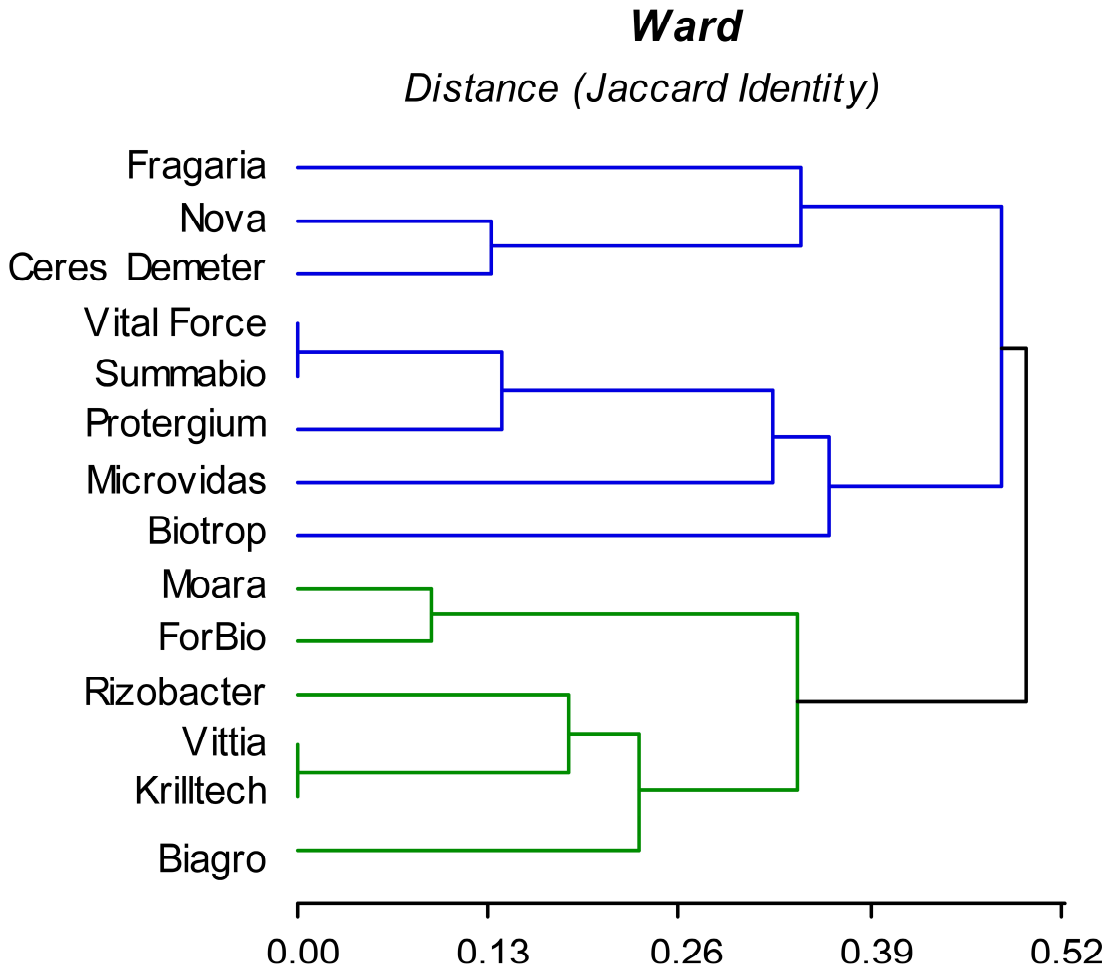

Figure 3. Cluster analysis of innovations developed by interviewed companies in Argentina and Brazil. The two main formed groups are in different colors.

5. Discussion

The publicly available official data revealed a large number of inoculants, bio-fertilizers, and bio-pesticides registered in Argentina and Brazil. However, since the process of having a product registered takes around three years, official data provide an important but not updated understanding of the existing innovations in the field of bio-inputs. Up-to-date information on commercial products' developments was provided by the interviews with companies investing in bio-input innovation in Argentina and Brazil. In addition to efforts to develop more efficient inoculants and to master the formulation of bio-fertilizers and bio-pesticides, the interviews revealed ongoing developments of new commercial bio-inputs such as phytovaccines and bio-herbicides, as well as specific metabolites isolated from microorganisms (instead of the alive microorganisms), products for livestock, and the use of industrial processes such as lyophilization in product formulation (Figure 4).

The literature reveals different generations of technological development in bio-inputs, ranging from inoculants based on a single isolated bacteria [6] to more recent products using a pool of microorganisms or technologies such as molecular biology [11]. The scientific literature also publicizes experimental developments on products such as bio-herbicides that can become the next generation of bio-inputs [19].

The results for Argentina and Brazil reveal that while some companies and research centers focus on improving the quality of existing products, such as inoculants, to compete in a large-scale existing market, others invest in developing new products targeting specific markets where exclusivity may guarantee greater profit margins. Therefore, by looking at the end of the product development pipeline, we found different parallel and contempora-

neous technological races for product development that can lead to important progress in the bio-economy [27].

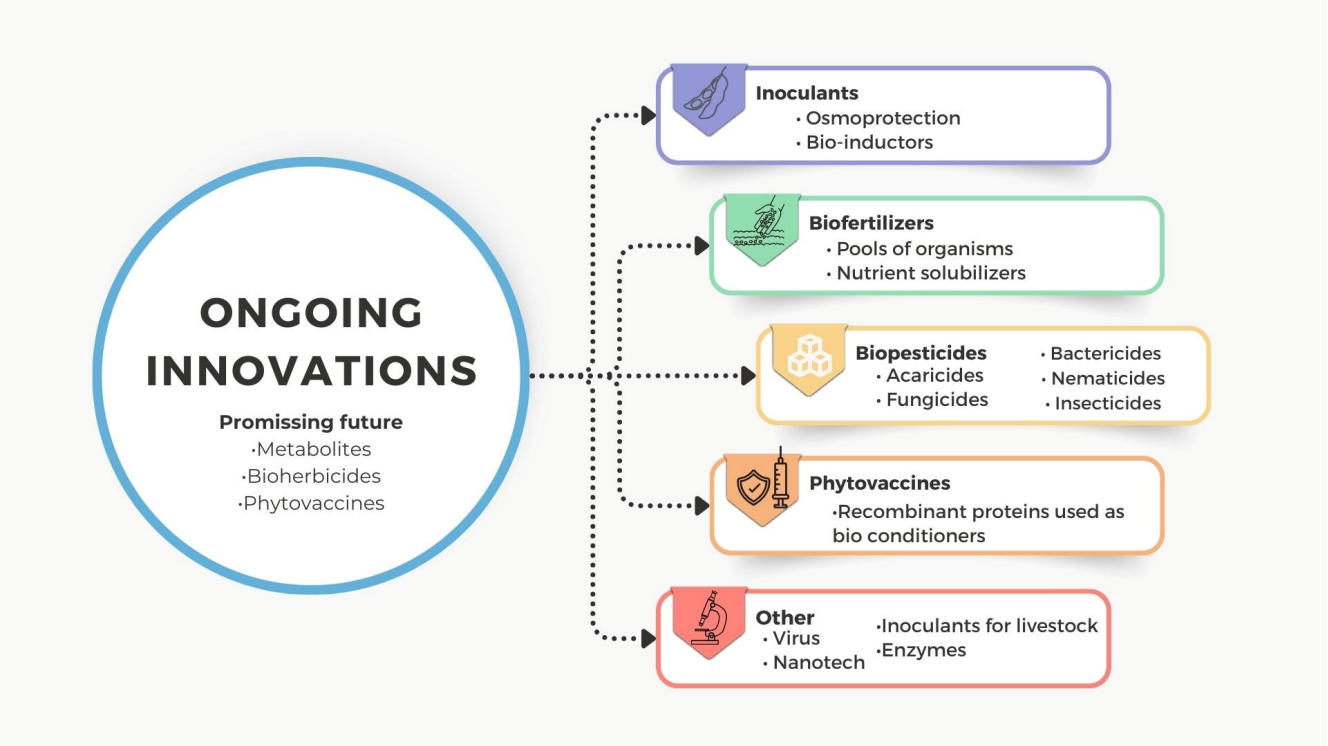

Figure 4. Summary of ongoing innovation fronts in agricultural bio-inputs taking place in Argentina and Brazil.

Consequently, we do not have new generations of bio-inputs replacing the old generations as if in a technological continuum of new technologies taking the place of the old ones, but we rather have parallel races for the improvement of existing products and the development of new products for different markets happening at the same time. The value for money and the efficacy in different field situations of these innovations in bio-inputs [6,12,15] will define the products that may remain on the market over time. Since any technological development and its adoption can be associated with potential risks, especially when living microorganisms are released into the environment, corporate accountability and continued academic research are fundamental for this sector in the long term.

These parallel races may potentially result in innovations that address market demands and can lead domestic companies in Argentina and Brazil to establish themselves in the market for agricultural bio-inputs. The rising global demand for agricultural products creates opportunities for investments in innovative agro-industrial sectors [31]. Since cooperation for innovation between private companies and research institutes is particularly beneficial for domestic high-tech companies [35], the bio-inputs sector can largely benefit from investments made by both private companies and public research centers [34].

The limitations of this study include the relatively small number of companies interviewed. Despite the importance of the bio-inputs sector in Argentina and Brazil, there are still no country-wide updated sources of information on the main sector trends that can guide assertive investments in product development and market expansion. Key market-related missing information includes:

- Main public innovation centers—List of the main research teams alongside the most important research centers (organizations/laboratories/researchers) and their recent developments on bio-inputs. This information is available for Argentina [24], but not for Brazil;

- Companies with commercial products—Description of companies with products registered and technologies currently available and under development (with their technology readiness levels—TRL);
- Bio-inputs market—Survey of the volume and values sold by type or group of products (such as bionematicides) and regions;
- Current adoption by farmers—Interview with a sample of farmers nationwide on adoption levels;
- Potential adoption by farmers—In-depth survey with farmers in a region where there are high adoption levels to identify the ideal/possible level of adoption per crop given the existing solutions in bio-inputs;
- On-farm adoption by farmers—Assessment of the on-farm production (on-farm bio-factories) sector, including its size (number of companies), distribution (by state), and adopting farmers' profiles.

6. Conclusions

The results of this study reveal ongoing development efforts to improve traditional agricultural bio-inputs such as inoculants, to master the formulation of new products such as bio-fertilizers and bio-pesticides, and to develop the next generation of bio-inputs such as phytovaccines and bio-herbicides. Private companies, in collaboration with public research centers, are leading innovations on these different fronts by targeting different market opportunities with potential for important contributions in terms of bio-economy growth. Taken together, these developments already provide more efficient commercial inoculants to improve the biological fixation of nitrogen in soybeans, as well as new inoculants for cereals such as wheat and corn and in fruits and vegetables. Bio-fertilizers made of pools of microorganisms resulted in commercial products to induce plant growth and solubilize soil nutrients. Bio-pesticides are also available on the market as bio-acaricides, bio-fungicides, bio-bactericides, bio-nematicides, and bio-insecticides.

Ongoing developments promise the next generation of agricultural bio-inputs, such as phytovaccines to activate the plant's immune system and bio-herbicides to potentially replace synthetic chemical herbicides in preparing fields to be harvested. The use of industrial processes such as lyophilization also allows the formulation of powder instead of liquid commercial products, which reduces the logistical costs.

Domestic stakeholders have an important role in these technological developments. The official records show that both foreign multinationals and domestic private companies lead in the number of products registered in Argentina and Brazil. The survey conducted with the domestic companies reveals their leading role in the different innovation fronts described in this study that can lead companies in Argentina and Brazil to establish themselves in the global market for agricultural bio-inputs.

Potentially disruptive innovations such as bio-herbicides, phytovaccines, and isolated metabolites extracted from microorganisms can underpin bio-economy growth globally. The sector of agricultural bio-inputs can be seen as an opportunity for developing countries to go beyond the primary production of agricultural commodities and build new agro-industrial capabilities for sustained agro-industrial growth.

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