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The emergence of microbiological inputs and the challenging laboratorisation of agriculture: lessons from Brazil and Mexico

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Abstract
In this article, we analyse the tensions associated with the emergence of microorganism-based agricultural inputs in two Latin American countries, Brazil and Mexico. More specifically, we examine the ways in which these technologies, which are based on the use of living organisms, leave public microbiology research laboratories and are further developed by manufacturers or farmers. To this end, we draw on the concept of the 'laboratorisation' of society, part of the actor-network theory. We show that the emergence of these technologies is currently facing a number of challenges, due to the risks associated with their biological nature and the difficulty involved in establishing production processes as reliable as those used in reference laboratories. Whether produced by companies or on farms, the quality and safety of the practices and of these products are the subject of debate, as well as the focus of scientific, economic and political scrutiny. These microbiological inputs are evidence for the transformation of the relationship between science, industry, users and politics that is taking place around the emergence of alternatives to synthetic chemical inputs in agriculture, and more broadly, about the use of microbiological resources in agriculture.

Keywords Agricultural inputs · Microorganisms · Innovation · Technology · Laboratorisation · Latin America

Introduction

As a way to reduce agriculture's dependence on chemical inputs, biological inputs have major technological potential. Biocontrol products and biofertilizers, which were previously limited to technological niches and alternative farming systems, are currently making their way in large scale production systems. There are a number of reasons for this change: the rising cost of chemical inputs, particularly fertilisers, recently accentuated by global geopolitical instability (Matthews and Grové 2023; Brownlie et al. 2023); economic and political pressure to reduce the health risks and environmental impacts of industrial agriculture (FAO 2023); the development of companies that manufacture biological inputs and the availability of an expanding range of products on the market (Le Velly et al. 2023); or incentive policies aligned with the debate on more sustainable agri-food systems (Place et al. 2022), promoting, for example, the production of biological inputs in biofactories located on the farms themselves (Bullor et al. 2023).

Among the wide range of technologies involved, those based on microorganisms, used both as biofertilizers and for biological control, have been the subject of outstanding growth (Goulet 2023; Goulet et al. 2023). These microscopic bacteria or fungi, applied to soil or plants, help the latter to capture nutrients, strengthen their defences against disease, or act directly on pests thereby controlling their population. The growth of these technologies reflects the increasing attention being paid to microbiota in agriculture, particularly in soil management (Granjou and Phillips 2019), and more generally with the growing promise of the bioeconomy (Mittra and Zoukas 2020; Delgado 2024).

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Microorganisms are considered as allies which can perform productive tasks in agricultural or industrial systems (Paxson and Helmreich 2014; Daniel 2023), but with characteristics that differ radically from those of conventional inputs or technologies. Their application conditions, the temporality and intensity of their effects, but also the fact that they can be relatively easily produced by users or amateurs (Pilizota and Yang 2018), outside "traditional" laboratories, are among the most notable of these characteristics. The ways in which they differ from chemical inputs raise questions about the concrete conditions of their emergence and widespread use in agriculture. As already shown in other sectors (Geels and Schot 2007), the emergence of alternative technologies involves much more than a logic of substitution: it implies a reconfiguration of the socio-technical systems in which the technologies are embedded.

By emergence, we mean the processes which at an early stage and by involving a diversity of stakeholders (research, industry, public administrations, distributors, users, etc.), contribute to the spread of a technology thereby rendering it important, even predominant (Rotolo et al. 2015). In the case of micro-organism-based agricultural inputs, the conditions of this emergence need to be considered in the light of two characteristics. Firstly, there is the question of how these technologies can be "transferred" from laboratories to companies or biofactories on farms. Indeed, until now, microorganisms have mainly been the subject of research by laboratories belonging to agricultural research organisations, mainly conducted by specialists in microbiology and biotechnology. Secondly, the conditions of emergence - and hence of leaving the laboratory– need to be considered in the light of the biological nature of the technologies concerned.

In the Cambridge dictionary, the term '*biological*' refers to entities that are "*about or relating to living things'*. Their living nature induces phenomena of reproduction, growth and senescence that make them a priori less easy to control and subsequently less standardised than non-living entities, such as synthetic fertilisers or pesticides. Biological entities are also subject to spontaneous physico-chemical transformations making them perishable and creating uncertainty, but also to the risk they may escape (Bauer-Panskus et al. 2020). Leaving the laboratory or experimental stations involves loss of control, even if only partial, over these entities; scientists and users must therefore exercise a certain amount of control over these allies, both to avoid excesses and to ensure they are productive (Daniel 2023). Faced with imaginary fears and proven risks, scientists and industrialists usually try to understand citizens' and users' fears concerning biotechnologies in order to allay them (Bauer 2002), and to consider their social acceptability (Gupta et al. 2012). In economic sociology, particularly in social studies of the organisation of markets for agricultural products, a few authors have highlighted the fact that the perishable nature of agricultural goods can influence the nature and organisation of markets (Chance et al. 2023). However, despite the literature on downstream production, the way in which technologies used upstream as 'lively commodities' (Barua 2017) emerge and leave the laboratory remains unexplored. Above all, while the cognitive and political dimensions involved in moving the production sites of these bio-based technologies out of the laboratories have been documented in other sectors (Meyer 2013), elsewhere they remain uncharted.

The objective of this article is to fill this gap, by focusing on the dynamics of the leaving of these microscopic beings from the laboratory and their movement towards biotechnology companies and farms. Today, the scientific and industrial uses of living organisms and their agricultural applications are at the intersection of economic, ethical and political issues (Busch et al. 1992), and are particularly controversial, as illustrated by the case of GMOs from the 1990s onwards (Levidow 1999; Marris et al. 2005). The aim here is to pay close attention to the debates, frictions and controversies that are accompanying the emergence of these microorganism-based technologies, with a particular focus on the new division of labour between the main players in agricultural science and technology. We more specifically consider the cases of two Latin American countries, Brazil and Mexico, where microbiological inputs have recently attracted the attention of stakeholders of the agricultural sector.

The article is organised as follows. First, we review the debate about how technologies and innovations are transferred from the laboratory to industry and to users, in particular by examining the features of technologies of biological origin. We take the opportunity to emphasise the concept of laboratorisation of society, part of the actor-network theory, which we use more specifically to shed light on the field data. Section 3 describes the methods and materials used for this research. The results are presented in two parts that embody two distinct modalities of the laboratorisation of society. On the one hand, the forms of connection between science and the microbiological input companies; on the other hand, the dynamics and tensions associated with the on-farm production of microorganisms by farmers, and the controversies they raise concerning the relationship between science, policy and society. Finally, we discuss these results and conclude by suggesting avenues for further research.

From technology diffusion to the laboratorisation of society

The relationship between scientists and engineers who design technologies and their potential users is a long-standing area of research, in which the relationship between science and society has been examined from many angles. Past studies of the diffusion and adoption of agricultural technologies have, for instance, looked at the way technologies are disseminated within societies over time, and characterised the profiles, motivations, and rationalities of adopters (Rogers 1962). This approach has been criticised for its linear nature and Taylorist interpretation of innovation. Works on the role of users in innovation have highlighted the possibility that new ideas may come not only from the laboratory and scientists, but also from citizens (Von Hippel 1976), or, in the agricultural sector, from farmers (Chambers et al. 1989; Dolinska and d'Aquino 2016).

For their part, co-innovation (Saragih and Tan 2018) and co-design (Meynard et al. 2012) approaches have emphasised the porous nature of laboratory boundaries both in the design stage of innovations and technological diffusion, which supports the idea that scientists and users collaborate to create and subsequently to adapt technologies to each societal context. These kinds of collaborative models now permeate approaches that call for the democratisation of innovation and science (Von Hippel 2005; Elmquist et al. 2009), emphasising the role of lay people. However, the incorporation of users and citizens frequently fails to account for the diversity of stakeholders and institutions involved in the development of the technologies and innovations concerned. Forms of collaboration between science and industry (Ankrah and Al-Tabbaa 2015), the triangular relationships between science, industry and public policy captured by the triple helix model (Leydesdorff 2000), to which, civil society is added in the quadruple helix model (Carayannis and Campbell 2009), try to capture this diversity. Like the innovation systems approach (Lundvall 1992), these different approaches are based on the premise that scientists and engineers are not the only actors capable of generating technologies and innovations. The interactions and collaborations they pursue along with other stakeholders are the main forces that boost innovations and push the knowledge they create out of the laboratories.

These interactionist approaches converge with those that have emerged in Science and Technology Studies (STS) on the social construction (Bijker and Pinch 1987) or social shaping (Williams and Edge 1996) of technologies, and more broadly with the Actor-Network Theory (ANT), which makes it possible to gain insights into the diversity of actors involved in the expansion of a technology, at the interface between a laboratory and society. According to ANT, what makes an innovation successful is not just its technical relevance or economic efficiency, but the translation processes by means of which certain actors - equipped not only with ideas and discourses but also material and technical instruments such as reports, standards, guides, tests, Petri dishes - try to convince different stakeholders that their interests are aligned with the development of the innovation (Callon 1986; Akrich et al. 2002). Therefore, technologies and their expansion involve the construction and extension of sociotechnical networks and arrangements that create entanglements between actors and non-humans. As close as possible to the technologies and their uses, these sociotechnical phenomena involve reciprocal adjustments between the technologies and their environment. Technologies are not simply 'adopted': they may be adapted and transformed by users, in the same way as the technologies affect their environment. Technical objects thus carry with them scripts (Akrich 1992), which predetermine a certain number of conditions under which users and actors outside the design process will have to act.

Based on his analysis of Louis Pasteur's work on microorganisms, Bruno Latour showed that technologies never really leave the laboratory and enter society: rather, society incorporates the characteristics of the laboratory to accommodate the technologies (Latour 1988). In fact, it is the extension or replication in society of the material conditions and working methods that usually prevail in the laboratory which enable the expansion of technologies designed in this controlled environment. This is what, following Latour and his 'Pasteurisation of France', Callon, Lascoumes and Barthe, termed the "laboratorisation of society" (Callon et al. 2011). They show that researchers are not antisocial scientists who isolate themselves in their laboratories with one aim, i.e. to develop technologies, rather they are social actors who play an active role, particularly in interactions with funding bodies and public decision-makers, in rendering the world receptive to these technologies. The success and emergence of the technologies they promote depends to a large extent on the creation of replicas of the laboratory outside the confines of the academic world. For instance, the emergence and success of the vaccines designed by Pasteur in his laboratory were based on training doctors in bacteriology and hygiene, and on installing the necessary instruments and conditions for storing and applying the vaccines in their practices. Thus a whole range of equipment and knowledge together form the infrastructures (Star 1999) and replicate the laboratory conditions that are required for the emergence and diffusion of technologies from the laboratory into society. The dynamics highlighted by Bruno Latour apply far beyond the case study he analysed, and are relevant to many technologies and innovations. However, the question of microbes and microorganisms remains an exemplary case, highlighting what is feasible under laboratory conditions and what is not feasible elsewhere. First and foremost, it's the ability to isolate and control living organisms that are invisible to the naked eye, and which might otherwise escape notice. Secondly, as Latour points out, it enables us to make these entities visible through inscriptions, and to act upon them.

This seminal work on laboratorisation not only invites us to rethink the very idea of "leaving" the laboratory, but also, through the case study analysed by Latour, to question the possible specificities of mechanisms that enable technologies based on living organisms to thrive outside laboratories or experimental stations. At first sight, one might consider that the specifics are null, so much so that the deployment and diffusion of such technologies - for example improved varieties of cultivated plants (Ryan and Gross 1943) - were reference cases for the first works in the field of diffusionist approaches. In agriculture and livestock breeding, the large-scale dissemination of improved animal breeds and plant varieties (Fabrice 2019; Byerlee 2020) was a textbook example of this massive outflow of biological technologies from laboratories over the course of the 20th century. But one of the reasons for this success is precisely the fact that these biological entities have undergone processes of standardisation, stabilisation and commodification (Barua 2016; Smessaert et al. 2020), thereby helping to reduce their unpredictable nature and variability. Advances in genetics have been essential to this trajectory, but not only: it has also depended on the development and promotion of a whole range of technologies surrounding these living entities - the famous 'ready-to-use' technological packages, including fertilizers and pesticides in crop production, for example - that have enabled these entities to prosper. But resistance to this well-oiled mechanism of commodified living expansion has since emerged. First and foremost, it is living beings and nature itself that have reminded humans of their existence with, for example, the sensitivity of these beings to health pressures outside the laboratory leading to the ever-increasing use of pesticides or antibiotics, or to the ever-tighter confinement of factory-farmed animals in spaces that are just as confined as laboratories (Hinchliffe and Ward 2014). It is also humans who have become engaged, applying a political register to criticize the impoverishment of biodiversity engendered by these transformations, and claiming the right and capacity of citizens themselves - farmers, for example - to ensure the conservation and improvement of biological resources (Kloppenburg 2004). The era of genetic modification in the laboratory has brought this contestation and the reaction of experts into the realm of risk management and risk prevention: whether for genetically modified plants or insects (Levidow and Tait 1992; Reis-Castro and Hendrickx 2013; Schwindenhammer 2020), the transition from the laboratory to the outside world has thus become an issue of "release" into the environment of entities that have become suspect. More than ever, these technologies and their release from the laboratory have become political objects, both for citizens, for the professionals who use them, and for the actors in the political field who are obliged to deal with them (Schwörer et al. 2023).

As we have seen, innovation and the emergence of living entities from the laboratory are complex questions, highly sensitive to the relationship between science, technology and society, and to how this relationship has evolved over time. More recently, this evolution has gone hand in hand with a transformation in the very way living entities and their role are perceived from whichever side of the boundaries between laboratory and society. From inert commodities, they have become recognised for the work they do and for their vitality (Barua 2019; Beldo 2017). In addition, the boundaries between laboratory and society, or between the different categories of actors empowered to work on biological objects, are also shifting due to the development of participatory science (Schrögel and Kolleck 2019) or do-it-yourself biology (Meyer 2021). These movements call on the ability of citizens to deal with these biological entities, all once again anchored in mobilisations tinged with epistemic and political claims.

In this changing context, marked by a renewed role for nature-based technologies, the transformation of the relationship between science and society, and the increasing political anchoring of innovations, the objective of this article is to better understand how microbiological technologies originating in academic circles are emerging at a large scale and are proceeding towards industry and the end users, in this case, farmers. To this end, the following sections draw on previous works associated with ANT to analyse one particular process of laboratorisation.

Materials and methods

The research on which this article is based was conducted in Brazil between 2019 and 2023, and in Mexico between 2022 and 2023. The aim of the research was to understand the driving forces behind the emergence of biological inputs in the two countries, based on interviews with the main stakeholders involved in biological inputs. A total of 44 interviews were conducted, 23 in Brazil and 21 in Mexico. Seven with farmers who produce and/or use microorganism-based inputs (State of Rio Grande do Sul in Brazil and Sonora in Mexico); 9 with employees of companies that produce and sell microorganism-based solutions; 3 with agents of companies that produce and sell solutions for on-farm production of microorganisms in Brazil; 3 with retailers who sell both chemical and biological agricultural inputs; 8 with officials from the Ministry of Agriculture and regulatory agencies in the two countries; 4 with independent consultants specialised in providing agricultural advice on bioinputs; and 9 with researchers in microbiology, entomology or agronomy. A snowball approach (Parker et al. 2019) was used to select the sample of actors interviewed. The best-known ones on the subject were first identified through an internet search or through our professional contacts; the interviews we conducted with these first actors then enabled us to identify and interview other significant players.

In addition to the interviews, in 2021, observations were made in Brazil during a three-day field trip accompanying a technician from a Brazilian on-farm solutions company, as she interacted with her farmer customers in the state of Rio Grande do Sul. In addition, we took part in two online events in Brazil, one in 2020 and one in 2021, which included debates on the rise of on-farm production in Brazil, in the presence of representatives of the biological inputs sector, farmers, researchers and Brazilian government officials. Finally, we examined institutional documents produced by public administrations and by private companies in the sector in both countries.

The recordings of these interviews and events were transcribed, and the most relevant elements were classified in twelve analytical categories dealing with the relationship between science and industry, science and policy, farmers' motivations and career paths, and the legislative framework for biological inputs and how it is evolving. These categories were established inductively, using a grounded theory approach, on the basis of all the data collected, so as to gather the most relevant material in a single working document.

Ensuring the continuum between science and industry

Research on microorganisms and their applications for plant nutrition and health has expanded considerably in recent decades. In the case of biofertilisation, there was a boom in research on biofertilisation and its applications in the mid-1990s, mainly in South America, with the development of soybean crops and the search for bacteria capable of fixing atmospheric nitrogen and transferring it to the plants. Using microorganisms for biological control is a more recent topic (Syed Ab Rahman et al. 2018), as biological control was long dominated by work on macroorganisms as the main tool for agroecological crop protection or integrated pest management, both of which combine biocontrol and chemical pesticides (Deguine et al. 2021). In Mexico, a public institution, the National Reference Centre for Biological Control, was created in 1991 whose mandate was to produce and transfer technological alternatives to pesticides. Although the centre initially focused on macroorganisms, a real turning point came in the mid-2000s, with the discovery or laboratory improvement of the properties of certain bacteria and fungi. In terms of biological control, these microorganisms offer farmers new possibilities; they are less restrictive than agroecological crop protection, which requires in-depth redesign of production systems, as a scientist from the Mexican National Research Institute for Forestry, Agriculture and Livestock (Inifap) pointed out: "*It is the closest thing to a chemical pesticide replacement. An application of Metaryzium, of Beauveria, or even Bacillus…. this can quickly replace a conventional application of a chemical pesticide*".

In Brazil, a similar movement has been underway since 2000, with microorganisms becoming a new common denominator for research on biofertilizers and biocontrol. In Brazil, organisational links are even tighter, with, for example, the 2016 merger organised by the state-owned Brazilian Agricultural Research Corporation (Embrapa) of the national research portfolio on biofertilizers and on biocontrol into a single portfolio on biological inputs and a shared bank of microorganisms. Starting in the early 2000s, research and development conducted in the laboratory began to be transferred to the industrial realm with the emergence of numerous start-ups and spin-offs, with close links to public research laboratories and universities. This is particularly true in the Brazilian state of São Paulo. Installed near the city of Campinas, the Instituto Biológico provides strains of microorganisms for beginning companies who supply the market with biocontrol technologies for sugar cane cultivation. This is also the case of various companies in Mexico, including a biocontrol company set up by a citrus grower, incubated in the early 2000s at the Centro de Ciencias in the state of Sinaloa. Combined with supplying bacterial strains, this research centre provides quality control for the company via a seconded agent. This component is essential, as there is a risk that poor multiplication practices will result in solutions that are insufficiently concentrated, or are contaminated by pathogenic microorganisms. Similarly, in 2003, a biofertilizer company in the state of Morelos was established with a signed agreement between an entrepreneur and the Research Centre for Biological Nitrogen Fixation of the Universidad Nacional Autónoma de México. The company's founder describes this partnership and the importance of maintaining close links with research laboratories:

> *We drew up the agreement so that we could promote, disseminate, produce, market and research the topic of biofertilizers in collaboration with the centre. We originate from a research and production linkage and, over the years, we have developed it rather than moving away from it, quite the reverse, we have strengthened it. We have collaboration agreements with various institutions that all, in one way or another, deal with the subject of agrobiotechnology or sustainable and alternative technologies.*

The secretary of the Brazilian Association of Biological Control Companies[1] also discussed the importance of this proximity and collaboration between companies that produce microorganisms and research laboratories, while differentiating this technological field from that of macroorganisms used in biocontrol:

> *These are companies with completely different profiles; because there is a much greater need for technology in companies that work with microorganisms. For production reasons, because it's high-tech: you have to select the microorganism; you have to adapt the formulation. Not with macroorganisms. Insects, you just produce them. They don't have the same wide variability as microorganisms.*

Their closeness to science, this continuum between companies and research laboratories, is much vaunted by these companies. Communication campaigns and websites are full of references to science and research, photos showing Petri dishes, staff in white coats with protective goggles and masks, and gleaming laboratories with stainless steel benches, refrigerators and vats. Everything is done to emphasise that these companies rely on laboratories that comply with the strictest safety and hygiene standards, on a par with the laboratories of the most prestigious research institutes or universities. These long-established companies do not hesitate to denounce competitors who, unlike them, do not maintain close links with research and do not replicate the latter's protocols, which they believe are the only way of guaranteeing quality products. A Mexican entrepreneur in the state of Coahuila denounced what he called "charlatans":

> *There are many pirate products in Mexico. And all these pirate products are produced by companies that see the market opportunity, but don't invest in technology, they don't invest in laboratories, they don't invest in qualified staff. They just see a business opportunity. And the truth is that - the word is going to sound very ugly - but they are prostitutes in the market.*

In their view, these companies are jeopardising the emergence of microbiological inputs, and hence the entire sector, by not complying with laboratory standards. Beyond the production conditions, the way in which companies seek to demonstrate the efficacy of their products is also called into question. Since they are positioned in a market that offers alternative technologies, of which farmers are often already suspicious, they have a great deal at stake in providing scientific evidence of the effectiveness of their products. They usually call on private companies to conduct ad hoc studies. But as one Mexican agronomist from a research centre pointed out, the protocols used are often not sufficiently rigorous, and deviate from laboratory standards:

> *When I started to see the impact of biofertilizers, I saw that there was practically no scientific information, let's say, including experiments, with statistical analysis, repetitions, experimental design, and in fact, there were comparisons, where in my opinion, they were using the wrong control, not the normal dose of fertiliser (...) I never saw an experiment where they used the right control.*

From the production of microorganism-based inputs to the evaluation of their effects, the laboratorisation of society - in this case embodied by companies which produce or evaluate inputs - is an essential factor in the emergence of these technologies. Laboratorisation is even obligatory for long-established companies in the sector: without it, and the guarantee it represents for product quality, they risk compromising their fundamental interest in increasing sales. But the extent to which this is happening varies with the entrepreneurial sphere, and consequently seems to be jeopardising, or at least hindering, the robust and rapid emergence of microbiological inputs.

Biofactories, or the complex laboratorisation of farms

In addition to the relationship between research laboratories and private companies, another way of laboratorising the sector is succeeding in both Brazil and Mexico: the production of microorganisms directly on-farm, by farmers. As we will see, this approach has a great transformative potential, but is also deeply controversial in terms of the rigour of the laboratorisation.

Public programmes and private companies

One of the specific features of the Latin American continent is booming on-farm production of microorganisms by farmers, which began in the mid-2010s. This type of production of microorganisms, which in Brazil, is sometimes referred to as on-farm production, is embodied by the concept of biofactories at the regional level. With these biofactories, the aim is to achieve the process of laboratorisation by replicating the laboratories that produce microorganisms on farms, or in local units located close to farms. Farmers are interested in doing so for a number of reasons: in

[1] In 2020, merged with Croplife, an association of biotechnology, pesticide and germplasm industries.

areas with limited access to commercial companies, it gives them access to biological inputs; and for those who already have access, it gives them access to these technologies at a much lower price, in return for their initial investment in the required infrastructure. The equipment mainly consists of plastic or stainless-steel tanks, air circulation systems to facilitate aerobic multiplication, and sometimes cold rooms to store the resulting solutions. The equipment is usually located in a dedicated area on the farm, which most farmers call the *'laboratory'*, which contains everything they need to produce microorganisms including a microscope to observe the microorganisms, charts or notebooks in which information such as the temperature or pH of the solutions is recorded at regular intervals, fridges to store the strains, disinfection equipment, etc.

But farmers need to acquire knowledge on how to run these on-farm laboratories on their own, and in this respect, they are not being left behind, on the contrary, they are being trained through public training opportunities or thanks to agricultural development programmes at federal or state level - *Producción para el Bienestar* in Mexico, *Programa Nacional de Bioinsumos* in Brazil - involving researchers and technicians from Inifap in Mexico and Embrapa in Brazil. Informative documentation is also produced, for example in Mexico with a series of "*Practical manuals for the development of bioinputs*", that explain the basics and list the equipment needed to set up a biofactory.

Companies that specialise in setting up biofactories and supporting farmers also play a key role in these dynamics, particularly in Brazil. Two companies established in the mid-2010s are very involved in the process of laboratorising farms. They offer farmers a turnkey service, including production infrastructure, strains of microorganisms selected in laboratories, the growth solution needed to multiply them, hygiene products and, of course, advice and training. Their objectives are clear: to position themselves as laboratory brokers, bypassing traditional marketing channels for inputs, and to expand their market share at the expense of companies marketing micro-organism-based solutions. They position themselves as science and technology brokers for farmers, insisting, like their counterparts who market ready-to-use solutions, on the scientifically sound nature of their work. Their websites and communications materials show staff wearing white coats and gloves, workbenches and laboratories, and the "*advanced research centres*" they have recently built. The structures they install are described as particularly rigorous, complying with the strictest scientific and industrial laboratory standards. As one company website explains, they comply with "*pharmaceutical production standards*", "*air quality control [*is*] on a par with world-class hospitals*", and have "*networks of accredited external laboratories to guarantee quality control at every stage*" of production. The company draws attention to their "*scientific teams*", one of which has "*30 PhDs and 5 post-docs*". In 2022, the team took on board one of Embrapa's leading microbiologists, who had headed the national bio-control research programme, and who became the company's Director of Research and Innovation. All this scientific rigour serves one purpose, as emphasised by the two leading companies: "*to develop the ideal laboratory project for the farm*", and to enable the emergence of "*professional on-farm multiplication*" of microorganisms.

Criticism from scientists and industry

While the momentum in favour of biofactories continues in both countries, this does not exclude criticism from scientists and private companies who question the rigorous nature of this attempt to laboratorise farms. With scientific studies to back them up, microbiologists in public research institutes such as Inifap, Embrapa and universities in both countries are warning about the risks of multiplying pathogenic microorganisms, some of which are resistant to antibiotics, that would then be released in the fields. In an interview, an Inifap scientist explained: "*In our laboratories, we have evaluated products they say will include one strain… we evaluate them, grow them and all kinds of things grow, (…) we start the analyses, and there's a zoo growing right there*".

Given the expansion of such biofactories, scientists make every effort to underline the poor quality of the equipment and of on-farm practices, as well as the low level of qualifications of the people involved. For example, one scientist in Mexico pointed out that, despite the training provided by Inifap researchers, the technicians working on the *Producción para el Bienestar* programme are not capable of reaching the standards required by these technologies: "*The problem is that the technicians do not master the concept, that is the biggest problem they have. I had to teach some topics to technicians in the programme and they do not have the profile, some of them are not even agronomists, others are teachers*".

Yet, it is mostly the farmers' skills that are being called into question by scientists and industrial producers. The head of Embrapa's national microbiological nitrogen fixation programme put it bluntly: "*Farmers don't have the skills to work with microorganisms. Microorganisms are not for amateurs*". The professionalism of scientists and companies is held up in contrast to the amateurism of all those who have neither the skills nor equipment, or who allegedly do not respect the strict protocols recommended by research and industry. In the opinion of these actors, it is the boundary between scientists and non-scientists that needs to be preserved, as biofactories are in no way equivalent to what is practised or produced in 'real' laboratories. In so doing, they also seek to preserve exclusive rights to their field of knowledge and expertise, and of course, when the actors are companies, to defend their market share. In this way, they set themselves up as the "official" spokespersons for genuine laboratorisation, as the owner of a Mexican bioinputs factory put it:

> *Every activity requires scientific knowledge to back it up and that cannot be taken away. So, if I make someone do the task who knows nothing about the subject, he becomes a sorcerer's apprentice. Everyone can make biscuits or bread in their own kitchen, but setting up a bakery is another matter.*

In their communication materials, manufacturers emphasise their high level of technical expertise and professionalism, which sets them apart from laypersons who would expose the natural environment and consumers to the risk of contamination. As a manufacturer from the state of Morelos, in central Mexico, pointed out:

> *We have installed a hermetically sealed computer-controlled reactor there and the levels of oxygenation, stirring, etc., are controlled by the computer according to the requirements of the micro-organism. If we put Azospirillum, we know that we are going to produce Azospirillum and nothing else.*

It is in this way, and only at the cost of this strict and hermetic guarantee of good laboratory practices, that microorganisms would be able to work and the risk of jeopardising a promising industry, sources of employment and of income can be avoided. As the head of Croplife Brasil, the association of the agricultural inputs and biotechnology industries, pointed out, such technologies based on the multiplication and use of living organisms involve specific risks, and must therefore comply with the highest production standards. For instance, as high as those applied for decades to the production of chemical inputs, for which, because of the complexity of the processes and facilities required, such a move towards on-farm production has never been envisaged: "*We're not playing at mixing products in a tank with a broom, we're talking about technicalities. The rigour that applies to the control of traditional pesticides has to be the same for biologicals*".

Tensions between science and policy

An essential facet of this challenging laboratorisation is also present at the political level, and in the relationship that governments establish with the scientific sector. In both Brazil and Mexico, policies in favour of biological inputs have flourished under governments with conflicting approaches to science and academia. The Jair Bolsonaro government has been accused of massive disinvestment in science and technology, and more generally of disregarding the opinions of scientists on many subjects (da Cunha Bustamante et al., 2023). In turn, the government of Andres Manuel López Obrador in Mexico is often accused of seeking to bring the scientific apparatus to heel in the service of its policies, and of implementing a populist model of governance in the sector (Reyes-Galindo 2022). The case of public policies for the development of biofactories offers an unexpected window into these debates.

In Brazil, tensions rose in 2020, with the publication of Decree 10.375 establishing the National Bioinputs Programme, the main political instrument for the promotion of biological inputs by the federal government. In response to the article in this decree encouraging support for the creation of biofactories, the National Institute of Science and Technology MPCPAgro (Plant Growth Promoting Microorganisms for Agricultural Sustainability and Environmental Responsibility) published a particularly critical technical note. It criticised the government's "*simplistic*" attitude and its "*disrespect for science*", pointing out that the "*scientific advances*" made over the last few decades show that microorganisms are "*living organisms that require special precautions for handling and use*". It points out that the production of microorganisms requires "*knowledge of complex fermentation processes, high technological and microbiological knowledge and aseptic conditions to control microbial growth*", and "*several pieces of equipment, including an autoclave, a laminar flow hood, an analytical balance, a growth oven, a microscope, as well as an aseptic control room*". In other words, farmers would have neither the skills nor the material resources to replicate on-farm laboratories capable of multiplying microorganisms in a sufficiently controlled manner.

The confrontation between scientists and policy-makers continued in 2021 with the proposal for a bill to formalise the absence of obstacles or regulations, so that farmers can produce microorganisms on-farm. One of the aims of the bill was to guarantee that large-scale farmers, who were allies of the government at the time, would be able to continue to operate freely. At the time, increasing numbers of farmers were investing in on-farm production units, and were receiving support from the highest levels of government. Such support dates back to the previous government, under the presidency of Michel Temer, when the Minister of Agriculture was the country's largest individual soybean producer, and also produced microorganisms on-farm. At the time, the bill explicitly aimed to recognise and encourage "*a conduct that today is widely practised by the national agricultural* *production sector*", and to "*protect farmers*" with biofactories. At the time, the interest of the government was clearly to pledge its support to the lobby of large agricultural producers, and to its many political allies in parliament. Faced with this proposal, scientists also protested. This time it was Embrapa, even though it was under the political authority of the Ministry of Agriculture, who, in November 2021, published an official statement openly critical of this legislative process. The statement listed the risks associated with on-farm production when technical and sanitary standards are not met, including "*the proliferation of contaminants*", "*the pathogenic risk for humans, animals and plants*", and ultimately the risk of "*damaging the good image of bioinputs*". On the basis of these warnings, the scientists recommended that all producers of microorganisms should be recorded in an official register, and that farms should have an authorised technical manager. The Ministry reacted calmly to these "*alarmist*" calls from scientists, urging them not to get involved in politics. One official explained:

> *Embrapa has to focus on Science and Technology and Innovation, and the Ministry of Agriculture is concerned with monitoring. In the same way that I don't do research, I think Embrapa should concentrate on doing research. (…) In this case, I think it's better to let everyone focus on their own business.*

In Mexico, although the controversy has not reached the same level of publicity as in Brazil, the tensions are no less present. The main programme that promotes biofactories, *Producción para el Bienestar*, is part of the Sub-Secretariat for Food Self-Sufficiency, itself part of the Secretariat for Agriculture and Rural Development (Sader). Like the sub-secretary, who is close to the *campesino's* movement and an advocate of biofactories, the sub-secretariat supports the development of agroecological practices for small farmers. The concern for biological inputs within the programme is, according to its managers, an "*import*" into the Ministry of what has been practised in the field for years by NGOs defending agroecology for peasants. One of the programme's managers, whose career path has been at the interface between these organisations and committed university research, describes it in this way: "*We had already been practising it and agroecological organisations, organic farming organisations*, etc., *already existed that had been doing this. What we did was, let's say, make it a public policy that targets small farmers*".

The claim of being close to the world of NGOs also implies distancing from scientific organisations, or at least from some, and from a certain vision of the relationship between science and society. Inifap, for example, which has been developing biocontrol programmes since the early 1990s, only plays a secondary executive role in Sader's programme, with a few engineers and researchers involved in training the technicians responsible for supporting farmers. As an agent from the Sub-Secretariat pointed out: "*They didn't know about bioinputs, they are just starting… (…) They didn't have the researchers for this. We have had to get some*". On the other hand, the National Council for Science and Technology (Conacyt), a generalist institution that has been the subject of major political interventions by the federal government - an intervention which was denounced by a large proportion of the scientific community - is identified as a partner of choice. This is not just because of its expertise in agricultural microbiology, but also because of the transformation it has undergone in its relationship with society as a result of government policies[2]. The same agent from the Sub-Secretariat said:

> *Conacyt is doing things, Conacyt is our research entity. And they are participating more and more with us, because they have changed: instead of doing desk research, producing theses, or writing papers, they are doing more applied research. So they have started to link up with us. Getting academics out of their comfort zone has been difficult.*

Unlike the case of Brazil, the Mexican government's interest here is in implementing concrete measures in favour of small-scale producers, echoing the government's broader political agenda to support the poorest sections of society as a priority. But like in Brazil, and for similar reasons, the Mexican government's actions in favour of biofactories are nevertheless being contested by leading scientists in agricultural microbiology. Their protest is in line with that of officials from the Secretariat of Agriculture, who are involved in working groups to modernise the existing regulations on biological inputs. These groups were set up in response to growing demand from companies, more and more of which want to market biological inputs and call for legislation that differs from that designed for chemical inputs. Researchers and civil servants involved in these working groups denounce a two-headed State, which on the one hand tries to modernise the regulatory framework on the basis of scientific criteria, but on the other hand, intends to promote biofactories in rural areas with no concern for strict standards in the production of microorganisms. Referring to these diverging policies, a microbiologist involved in the working group for the regulation of biofertilisers

[2] On the relationship between science, agriculture and society under Latin American left-wing governments see the case of Argentina: Goulet (2020) Family Farming and The Emergence of an Alternative Sociotechnical Imaginary in Argentina. Science, Technology and Society 25(1): 86–105.

commented: "*Between what we are working on, updating the official Mexican standard, and this public policy, it is totally contradictory*".

In the opinion of the officials responsible for regulating pesticide products, such contradictions end up working to the detriment of manufacturers, who for their part would do their utmost to use good practices to produce microorganisms. One of these officials remarked:

> *I consider the problem to be more political than technical; it is very difficult to make them [*the manufacturers*] understand a series of elements. And in the end, it results in unfair competition on the market. Industry complaints concern exactly that, i.e. there are a lot of home-made products that have not been the subject of scientific rigour.*

At the intersection between political, scientific and economic issues, the laboratorisation of society to accommodate the emergence of microbiological inputs is therefore crystallising major tensions in the political field and within public administrations.

Discussion and conclusion

What are the drivers of and challenges to the emergence of microbiological agricultural inputs? In this article, we attempted to answer this question, focusing in particular on the redistribution of knowledge and tasks between stakeholders in agricultural science and technology, and the political frictions this redistribution entails. We have analysed the process of laboratorisation of society that has accompanied the expansion of agricultural microorganisms from research laboratories to biotechnology companies and farms in Brazil and Mexico in recent years. We have shown that laboratorisation follows contrasting paths, in which proximity to scientific standards is not only a variable, but also the subject of heated debate. The development of production processes that are as close as possible to laboratory standards is considered by scientists and industrialists to be a prerequisite for the successful emergence of these technologies and the further development of this important sector for the agroecological transition. In their view, if these microorganisms are not produced using precise and robust laboratory processes and protocols, their living nature carries a twofold risk. Either they die, because of poor production or conservation practices, and the solutions produced have no effect and, in this case, will compromise the reputation of biological inputs; or they are produced haphazardly, contaminated with undesirable microorganisms, which could have negative effects on the health of ecosystems, environments and even human beings. As Bruno Latour points out, these risks are heightened by the microscopic nature of the organisms concerned, which are invisible to the naked eye. Since it is impossible to assess their quality without laboratory equipment, the only real guarantee of the quality of the products is to ensure that they are as robustly produced as they would be in a laboratory, respecting strict quality standards. Science and its practice, its standards and its equipment, are therefore necessarily at the heart of the emergence of these technologies and the successful laboratorisation of the society on which it is based. Emergence is thus both a matter of moving between production sites - from laboratories to companies or farms - and a matter of replicating a set of equipment, knowledge and other protocols. This dual process is both enabled by the biological nature of the technologies concerned - farmers could not, for example, synthesise pesticide molecules on their farm - and constrained by the latter, as production processes are very strict due to the fragile and sensitive nature of these living beings. But, although based on the symbolic and regulatory authority of science, this laboratorisation is nevertheless the subject of heated debate, with some stakeholders defending contradictory positions and interests. In fact, laboratorisation and the importance it gives to science has become a political issue in the two countries featured in this article, Brazil and Mexico. For some stakeholders, the laboratory and its distance from society are the embodiment of a science that is not at the service of the 'real' world and hence of society as a whole. What is called for by these people, is a partial and simplified laboratory approach, which in some cases ends up getting the better of the scientists. The controversies surrounding these processes and levels of laboratorisation thus bear witness to the misalignments that can arise between the interests of the various players involved in a given technology, and which are ultimately expressed at different levels, be they economic, epistemic or political.

On the basis of these results, two points for discussion and potential opening emerge. The first stems from the fact that in this article we considered all farmers as being members of the same population, whereas, as is often the case, the question of technological change is being raised with increasing vigour in connection with smallholder agriculture (Glover et al. 2019). Smallholder access to technologies, in this specific case, to commercial biological inputs and the knowledge needed to use them, is often limited, as they lack the necessary economic resources or logistics. On-farm production can be a promising option in this context, but it is also in just these situations that practices are most likely to deviate from sanitary recommendations. Appropriate forms of laboratory training for these groups should thus be considered. The question of adapting technologies to smallholders (Van Loon et al. 2020), which is sometimes considered from the angle of the cost of technologies or their maintenance, in this case, largely shifts to the sanitary and biosafety risks associated with technologies based on living inputs. A recent study on on-farm food processing and on-farm slaughtering of animals provides some pointers in this area (Hultgren et al. 2018). Regardless, the most heated debates concern these sectors in which further research would be of great interest.

Finally, the case study invites us to reflect on the transformation of relations between science and society around technologies based on living organisms. In recent decades, there has been a debate about the social utility of public research, its ability to generate transformative change (Schot and Steinmueller 2018) and its impact (Blundo-Canto et al. 2018). Here, particularly with the development of biofactories, we have a special case where scientists find themselves not lacking impact, but on the contrary caught out by a transfer that escapes them, or at least is not occurring in the conditions they would have chosen precisely because of the biological nature of the technologies and inputs in question: whereas no farmer would be able to synthesise chemical fertilisers or pesticides on his/her own, because of the heavy industrial infrastructure that would be needed to do so, they can do it with microorganisms. This reluctance on the part of researchers echoes the literature showing that, in the past, researchers have opposed the use to which their work has been put, for example in the context of armed conflicts (Moore 2013); here we find ourselves in an in-between situation, between researchers' conviction of the value of their work for farmers and society, and their rejection of the ways in which technologies emerge and scale. This in-between situation gives rise to an original scenario, which raises questions about the contemporary forms of linkage between science, public policy and society in the context of agroecological transitions, about how to set up and scrutinise policy developments and how to contextualise ongoing research.

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