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Industrial Dynamics and Business Strategies in the Emergence of Agricultural Biological Inputs

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ABSTRACT

Biological products present a sustainable alternative to synthetic agricultural inputs, yet the industrial dynamics triggered by these solutions remain unexplored. This study examines the strategic responses of dominant agricultural input firms to the rise of biological solutions. Through qualitative textual analysis of press releases, company reports, and other public sources, we identify five key strategies followed by incumbents: portfolio expansion, marketing and distribution, technological complementarities, product development, and window of technology. These exploration strategies are pivotal in shaping the technological and market trajectories of sustainable innovations, particularly in a sector characterized by market concentration. While synergies exist between chemical and biological products, incumbents face challenges adapting to the distinct rationale of these products. This study offers practical insights for firms operating in this emerging market while underscoring how incumbents play a dual role in navigating adaptation challenges while influencing the scalability and commercialization of these emerging sustainable technologies.

1 | Introduction

The excessive application of chemical inputs for crop protection and synthetic fertilizers for crop nutrition is an important driver of greenhouse gas (GHG) emissions and other negative environmental impacts in the upstream segment of agri-food value chains (Crippa et al. 2021; Poore and Nemecek 2018). Thus, the evolution and transformation of the production system through the development of environmentally sustainable production alternatives is presented as a core action course to address the current environmental crisis (Fraser and Campbell 2019). In this context, biological agricultural inputs have rapidly developed in the last decade as a technological alternative to synthetic inputs that support more sustainable and nature-based food production (Ferreira et al. 2019; Soares et al. 2022).

Biological inputs[1] are natural solutions based on macroorganisms, microorganisms, and natural substances that help to improve plant nutrition (biofertilizers); enhance plant growth and stress tolerance (biostimulants); and control weeds, insects, and fungi (biocontrol) (Adesemoye 2017). These solutions reduce the need for synthetic fertilizers and agrochemicals applied in production while also providing a response for pest and weed resistance and increased abiotic stress brought by climate change (Deutsch et al. 2018; Jiménez et al. 2023; Lu et al. 2022). As a result, the market for biological solutions in agriculture has become highly dynamic and could almost double in the next

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5 years (Bloomberg 2023; Marrone 2023). Yet, despite the growth in this sector, its market value still pales in comparison to synthetic inputs, and farmer adoption of biological products is still low (Fiocco et al. 2022; McKinsey and Company 2022).

Prior works have examined technical and performance aspects of biological inputs, including biostimulants (Li et al. 2022; Povero et al. 2016), biofertilizers (Mitter et al. 2021; Schütz et al. 2018), and biocontrol products (Ayilara et al. 2023; Ratto et al. 2022). A second line of research focuses on farmer-level barriers, addressing topics such as farmers' acceptance and attitudes toward biological solutions (Mulugeta et al. 2024; Tensi et al. 2022), as well as the availability of information about these products and their compatibility with existing farming systems (Constantine et al. 2020). Finally, a third body of research examines how regulatory challenges in different regions critically influence the development of new biological solutions and their integration into farming systems (Goulet 2021; Kurniawati et al. 2023; Villaverde et al. 2014). However, the literature does not sufficiently cover topics related to innovation management and business strategy aspects linked to these new products and how the industrial dynamics in the agricultural input sector could shape the development and upscaling of biological solutions. In this paper, we collect and systematize information from publicly available sources to build a systematic compilation of interactions between firms in the agricultural input sector to address two research questions: (a) What strategic actions do incumbent firms in the agricultural input sector follow to introduce biological inputs in their portfolios? (b) What are the main technological and commercial challenges incumbent ag input firms face in developing markets for biological inputs?

Recent literature has shown that large multinational firms in agribusiness are already exploring the actions of smaller firms and start-ups to potentially benefit from their developments (Fairbairn and Reisman 2024; Mac Clay et al. 2024; Mac Clay and Sellare 2025). A consolidation process has occurred in most stages of global agri-food value chains, particularly in the agricultural input segment (Crespi and MacDonald 2022; Deconinck 2020; MacDonald 2017), and as a consequence, a limited number of global multinational corporations control distribution networks, establish technology cannons, and set commercial standards in the industry (Clapp 2021b; Deconinck 2021; Fuglie et al. 2012). In this paper, we hypothesize that the lagged adoption of biological products is related to industry dynamics because technology selection patterns are not independent of characteristics such as concentration rates, firm asymmetries, and market share dominance (Dosi et al. 1995; Marsili 2001). Thus, the corporate behavior and attitudes of the large multinational firms that govern the agricultural input markets may be critical for the final success of biological solutions. Our first goal is to describe and systematize the strategic interactions between incumbent agricultural input firms and companies in the biological segment, identifying the main strategic drivers behind these interactions. Second, based on the rationale of this set of strategic interactions, we explore and unveil the underlying technical and commercial challenges of introducing biological inputs on a large scale. Drawing from diverse public sources, we build a tailored repository that captures the landscape of strategic interactions between incumbent firms in the chemical crop protection and synthetic fertilizer sector and companies developing biological solutions. These interactions serve as observable and measurable manifestations of more comprehensive business strategies. Our methodology involves a systematic narrative analysis of news articles and press releases to identify and categorize the primary strategic motivations underlying these interactions.

In this paper, we reveal that biological solutions pose several challenges to agrochemical and fertilizer incumbent firms as they fall outside their technical and commercial competencies. These challenges include understanding the use rationale of these products (less standardized compared to chemicals), complying with new registration and regulatory requirements, developing new commercial arrangements, retraining their sales force, and developing new skills among their distribution networks to guide farmers in the use of these products. In response to increasing demand from farmers and stakeholders for sustainable agricultural practices, incumbents are implementing a mix of strategies to expand their biological solution portfolios and pipelines, structured through strategic corporate investments, firm acquisition, and collaborative agreements with companies that have specific expertise in biological solutions. Our findings reveal five key strategies underlying these interactions, including product portfolio expansion, marketing and distribution, exploitation of technological complementarities, joint product development, and potential exploration of windows of technology. This approach allows them to leverage complementary capabilities and bridge the gap between traditional agrochemical practices and emerging biological technologies. Our research provides insights into the industry transformation and the mechanisms by which incumbent firms adapt to new technology in global agri-food value chains.

2 | Incumbent Firms in the Context of Technical Change

From an industrial organization perspective, incumbents are firms that have been established in the market for a significant period, typically holding substantial market share and creating barriers to entry (McAfee et al. 2004; Porter 1980). From a technological standpoint, these firms often rely on their existing capabilities to sustain competitive advantages but may struggle to adapt to certain types of innovation (Christensen 1997; Henderson and Clark 1990). When faced with market threats—such as new products, emerging technologies, or new entrants—incumbents generally adopt strategies to defend and maintain their market positions (Christensen 1997; Teece et al. 1997).

Whether new and promising technologies make it to mainstream markets and become industry standard depends, to a large extent, on how incumbent firms react to the emergence of these technologies (Banholzer et al. 2019; Eggers and Park 2018). Firms use several learning strategies to explore new technologies outside their core capabilities, while they exploit their main strengths through internal research and development (R&D) (March 1991; O'Reilly and Tushman 2013). Exploration helps incumbent firms incorporate knowledge and capacities that may be hard to generate (exclusively) through internal R&D due to path dependencies (Dushnitsky and Lenox 2005; Hockerts and Wüstenhagen 2010). The decision on adequate technological exploration and sourcing strategies is critical for aligning innovation activities with overarching business strategies, as it determines a firm's ability to adapt to technological changes while maintaining its competitive position (Teece 1996; Teece et al. 1997). An excessive focus on the exploration of new technologies can turn risky and cause the incumbent to move away from its core competencies, but at the same time, an excessive attachment to the current technological paradigm in markets where the capacity for innovation explains a large part of the profitability could lead to the weakening or even loss of competitive position. This is also in line with the notion of pivoting, which is a way to adapt the corporate strategy and leverage innovation based on the firm's core competencies. Pivoting is a strategy based on exploration that helps a firm discover new technological processes without making (initially) irreversible commitments (Kirtley and O'Mahony 2023).

This pivoting process involves strategic decisions about the optimal approach to accessing new technologies while ensuring compatibility with the incumbent's current core competencies and product pipeline. Utterback and Abernathy (1978) describe the early stages of a new technology as a period of high uncertainty, where there is limited clarity on the appropriate allocation of R&D resources. During this phase, companies often prioritize low-risk approaches to acquiring new technologies. Strategic alliances are commonly preferred to explore these technologies under uncertain conditions (van de Vrande et al. 2009). Strategies like venture capital investments or purpose-specific agreements with other companies or research institutions significantly mitigate the financial burden and risks related to technological exploration, but the company has less control of the technology and a lower share of potential profits. Alternatively, companies may adopt more integrated models with higher levels of commitment, particularly when there is strategic alignment (Ortiz-Gallardo et al. 2013), sufficient absorptive capacity to integrate the new technology (Dushnitsky and Lenox 2005), or when technological knowledge and capabilities are distant and require a steeper learning curve (van de Vrande 2013).

During these strategic pivoting in pursuing technological exploration, an incumbent firm has to determine the right balance between the current core competencies and the leverage of new capacities, products, and technologies. This requires making decisions in (at least) two important dimensions. First, they must decide *to what extent they want to commit their current resources and capabilities to new ventures*. A seminal work by Roberts and Berry (1985) studies different strategies that companies pursue to enter a new business and evaluates these strategies according to the type of corporate involvement that is required. According to these authors, the decision is based on a combination of the familiarity a company has both with the technology itself and with the target market. Along the same line, Martínez-Noya and Narula (2018) state that strategic technology partnering may imply different degrees of collaboration. Some research ventures require a high degree of two-way active collaboration, so companies need to involve strategic capacities and even dedicated facilities. This is also related to the level of control that a firm seeks to have in specific research partnering initiatives. While in some cases there is no need for control and partners may cooperate as equals, if higher levels of control are required, then incumbent firms will have to involve additional resources (e.g., pursuing the acquisition of a target company) (McCarthy and Aalbers 2022). Along this line, van de Vrande (2013) examines the pharmaceutical industry and finds that companies often adopt balanced technology sourcing strategies, alternating between low-commitment and high-commitment approaches. These choices are influenced by factors such as technological proximity and the maturity of the technology. Similarly, Han and Kang (2021) analyze the pharmaceutical sector and explore how market uncertainty shapes the role of alliances in technology exploration. In the industrial sector, studies by Koc and Ceylan (2007) and Brem et al. (2014) reveal that firms tend to align their technology exploration strategies with their broader business strategies. McCarthy and Aalbers (2022) demonstrate that technology exploration approaches can evolve, potentially transitioning from low-commitment strategies like alliances to high-commitment strategies like acquisitions.

A second decision incumbent firms must make relates to the *degree of readiness of the products, capabilities, and technologies they want to develop* in their exploration process. In some cases, a company needs to enter an exploration strategy that provides quick results (in terms of market-ready products or solutions) to respond to clients' demands or pressure from shareholders. A company can access a ready-to-use strategic resource or acquire knowledge quickly and straightforwardly by adding specific capabilities to their own R&D departments, collaborating with other industry players in open innovation practices, or acquiring entire firms (Trott 2017). Sometimes, it may take longer to have a product ready, but the company can profit from leveraging skills and knowledge in their learning process, coupling new capabilities with those already existing in the firm (Cohen and Levinthal 1989, 1990). In other cases, companies may incorporate commercially ready solutions, but this reduces the chances of capitalizing on internal learning and development (at least in the short term).

In the next section, we describe the process of collecting and structuring the data and how we delve into it to find a typology of incumbents' strategic choices. For the purposes of this study, we define incumbent firms as well-established, dominant entities with a significant presence in the agricultural input sector (including crop protection and synthetic fertilizers). We will analyze those interactions using two main dimensions described in this section: *(a) the level of organizational commitment and (b) the level of market readiness that the strategy provides*, which are summarized in Figure 1. This will help us unveil and discuss the underlying reasons behind incumbents' actions and the main challenges prompted by biological inputs.

3 | Data and Methods

The first step in our methodology was to identify and list interactions between incumbent companies and firms developing biological inputs in the period 2009–2023. This timeframe is related to the moment in which large agricultural input multinationals started to show an incipient interest in the biological sector (Kling 2012). We broadly define "interactions" as (a) alliances, partnerships, or collaboration agreements; (b) corporate venture capital investments; and (c) acquisitions. For an incumbent firm, the decision to pursue interaction with a biological company is intrinsically strategic because it is related to how a company builds a competitive position in the market in terms of defining its activities and value proposition (Collis and Rukstad 2008). Thus, these specific interactions serve as observable and measurable manifestations of broader business strategies.

From an operational perspective, for the definition of incumbent companies, we circumscribed the search to the eight top-selling companies in the chemical crop protection and synthetic fertilizer industries. Even though the four-firm concentration ratio (generally known as C4) tends to be the most adopted criterium in industry structure analysis (Kvålseth 2022), we decided to capture the eight largest firms in terms of market shares, which is also a valid criterium (Bajgar et al. 2019; Sleuwaegen and Dehandschutter 1986), and has also been adopted in other studies that discuss concentration in the agricultural input industry (Fuglie et al. 2011). Because our objective is to capture the landscape of strategic interactions as comprehensively as possible, this extended criterium is particularly valuable because it enhances the robustness and relevance of our findings by offering a more representative view of the key players and their interactions—especially in the fertilizer industry,[2] which is more fragmented compared to crop protection. By evaluating the eight main firms, we captured almost 90% of the agrochemicals market and 35% of the fertilizer market, which is representative of the dominant firm segment in both markets. This is summarized in Table 1.

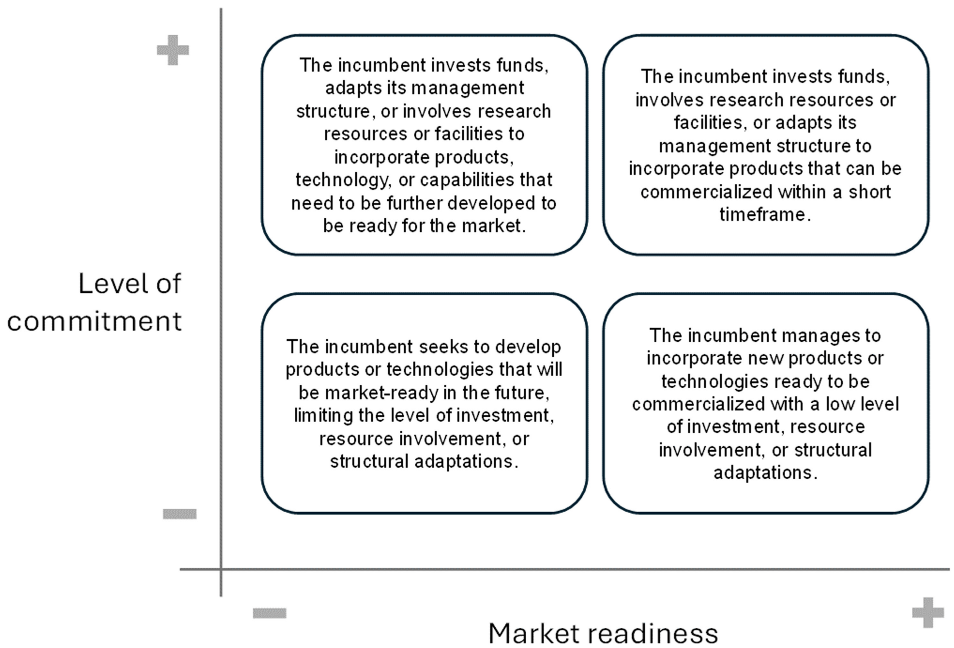

FIGURE 1 | Incumbent exploration strategies in front of new technologies. Level of commitment versus market readiness.

TABLE 1 | Leading companies in the chemical crop protection and synthetic fertilizer industry.

Agrochemical sales (2020)			**Synthetic fertilizer sales (2020)**		
	Value (in M US$)	**Market share**		**Value (in M US$)**	**Market share**
Syngenta (ChemChina) (incl. Adama)	15,336	24.6%	Nutrien (Agrium + PotashCorp)	9484	7.4%
Bayer (Monsanto)	9976	16.0%	Yara	9423	7.4%
BASF	7030	11.3%	The Mosaic Company	8014	6.3%
Corteva (Dow + Dupont)	6461	10.4%	CF Industries Holdings	4124	3.2%
UPL	4900	7.9%	ICL Group	3769	3.0%
FMC	4642	7.4%	PhosAgro	3351	2.6%
Sumitomo Chemicals	4010	6.4%	SinoFert	3099	2.4%
Nufarm	3491	5.6%	Eurochem	2945	2.3%
Total world market	62,400		Total world market	127,570	

Source: ETC Group (validated with Agbioinvestor).

We have drawn from several publicly available sources and specialized websites to build a systematic compilation of interactions between incumbents and biological firms. Although several commercial databases are available in the market, none of them allows for a comprehensive analysis of the three types of interactions we cover in this paper for the specific technological field under discussion. For instance, Dealroom and Pitchbook primarily focus on mergers and acquisitions (Retterath and Braun 2020). LSEG (formerly known as Refinitiv) delivers financial market news centered on asset and investment management industries. CB Insights is tailored to venture capital in select industries.[3] AgFunder, although specific to agtech and biotech, also covers mainly venture capital deals. Additionally, these databases do not offer open-access research-oriented alternatives.[4] Thus, we collect and synthesize information from several publicly available sources into a structured repository. To this purpose, we screen through (a) corporate press releases, (b) company websites, and (c) specialized business news sites such as AgFunderNews, Agribusiness Global, CropLife, PR Newswire, Business Wire, Reuters, and Bloomberg. We also run queries in the Google search engine and Google Finance. For venture capital investments, we also used Crunchbase, a comprehensive database of highly innovative public and private companies that is increasingly used for academic research, particularly in economics and management (Dalle et al. 2017; Mac Clay et al. 2024). Although the individual pieces of information are publicly available, their fragmentation made comprehensive analysis challenging. Our contribution lies in systematically collecting and organizing this information into a structured record tailored for this specific purpose.

The narrative analysis of corporate press releases, news sections in company websites, investor reports, and other pieces of media clippings has become common in the academic practice to understand industry trends, business strategy, or the effects of company disclosure (Chakraborty and Bhattacharjee 2020; Henry and Leone 2016; Huang et al. 2014; Hussainey and Al-Najjar 2011; Ibrahim and Hussainey 2019). Despite its qualitative nature, this type of textual and nonstructured information is valuable due to the insights it provides to explore the effects of company decisions. In this sense, press releases and business news clippings are nontrivial from a business perspective. The way in which a company communicates with the stakeholders is not an isolated decision but leverages the larger corporate strategy (Steyn 2003). These communication pieces have gained importance in the past years and may affect market value, investors' perceptions, and even prospective earnings (Chakraborty and Bhattacharjee 2020; Hussainey and Walker 2009; Shea et al. 2019).

One caveat in the analysis is that press releases and other corporate communication pieces (such as company reports or media articles) are usually based on a specific narrative style that is related either to persuade new potential investors or to engage with current stakeholders (Antioco et al. 2023). There is also an opportunistic use of press releases, which are used in the framework of a firm communication strategy and may be biased (Guillamon-Saorin et al. 2012). The specific narrative style of press clippings is based on influencing perceptions and does not necessarily disclose a company's deeper strategic intentions, which may be confidential. While aware of these limitations, we still rely on these types of information as a source to systematize information. Companies following innovation-oriented strategies, normally more exposed to a higher risk level, tend to use voluntary disclosures through press releases more frequently (Bentley-Goode et al. 2019). These companies do this to gain attention and greater coverage (which, in the end, is critical toward securing funds), but this also relates to reducing information asymmetries between company ownership and management levels.

We have structured a systematic approach for the search strategy, as shown in Table 2, making the necessary adaptations and adjustments for each of the sources that we consulted.[5] Then, we followed a snowballing strategy of finding new interactions from the documents that had already been identified. Once we listed all these interactions, we downloaded the press releases, relevant news articles, or media clippings for each of them. We only considered English-language information, assuming most of the press releases and sources consulted target an international audience. We included articles that included at least an incumbent firm (considering the practical definition presented in this section) and a mention of a firm with expertise in biological solutions. Some ambiguous cases were captured in the search but excluded from the final compilation (e.g., interactions taking place among two small biological firms, where the involvement of an incumbent firm was not apparent, or between a small biological firm and a biotech service provider).

Our list of interactions includes 80 deals that involve agricultural input incumbents and companies developing biological inputs in the period 2009–2023.[6] Approximately 32% of these agreements were acquisitions; 39% were partnerships, alliances, or collaborations; and 29% were corporate venture capital investments. As shown in Figure 2, most of those interactions have occurred in the last 3 years, when biological inputs started to rise in consideration as solutions within agrifood value systems.

After identifying and systematically compiling the interactions, as a first exploratory step, we built a network to visualize the most active incumbents in terms of interactions and how they relate to biological firms. For this purpose, we combined directed and undirected connections (Bohemier and Chryst 2016). A directed approach was used for investments and acquisitions, in which the edges originate in the investors (or acquirer) and end in the companies receiving the investment (or being acquired). We used an undirected approach to visualize alliances,

TABLE 2 | Search strategy.

[incumbent name]	acquisition OR partnership OR agreement OR contract OR alliance OR investment	biologicals OR biological solutions OR bioinput OR biocontrol OR biofertilizer OR biostimulants

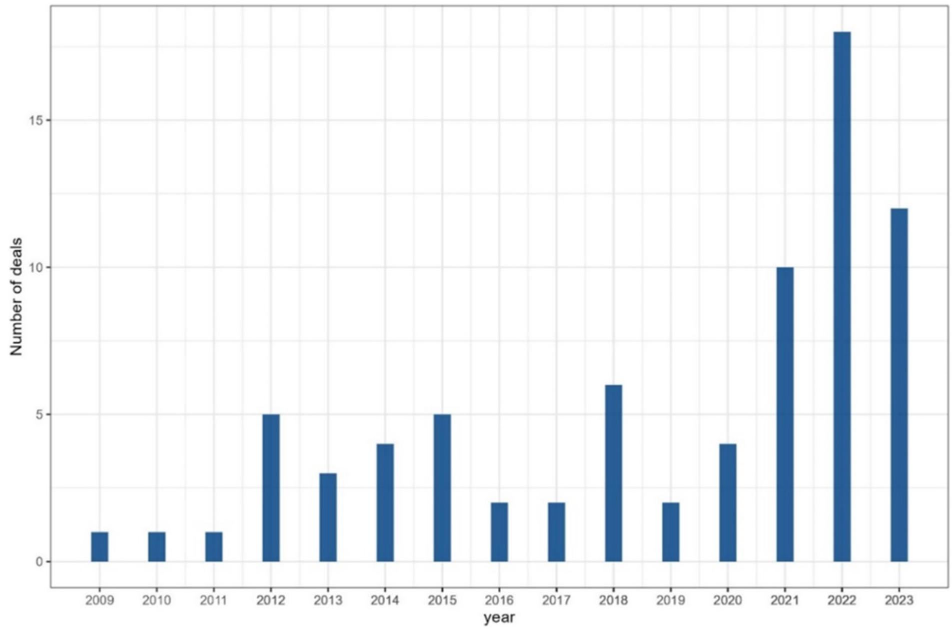

FIGURE 2 | Evolution of the interactions among incumbents and biological firms.

partnerships, agreements, or joint ventures. This network analysis helps to quickly visualize the most central incumbents pursuing a strategy toward biological solutions. We use the *igraph* package for calculation purposes (Csardi and Nepusz 2006).

Following the initial visualization exercise, we performed a detailed narrative analysis of all press releases and news articles using Atlas.ti.[7] The primary focus was to identify the strategic motivations and purposes driving interactions between the incumbent and the biological firm in each case. The lead author of the paper was in charge of the coding process, using a rigorous systematization process based on inductive coding. We began with an open coding phase, where we freely coded numerous quotes, searching for initial insights regarding the purpose of the agreement and the technologies and products involved. These initial codes were then refined through an iterative process and consolidated into a more systematic and coherent set, ensuring consistency in style and wording. Each document then reflected a set of codes which, after this refinement process, exhibited systematization and consistent wording structure. In the next step, we examined patterns among the codes, grouping them into broader, more comprehensive categories that reflected the strategic motivations of the interactions. Additionally, to mitigate the risks of subjective interpretation, a second co-author, with extensive industry experience, reviewed and validated the final classification. These specific codes and quotes, and how they build the final categories, are presented in Appendices S1 and S2. Finally, in each document, we coded the type of interaction (investment, acquisition, and alliance–partnership) and noted whether a specific biological solution was mentioned (biocontrol, biofertilizer, and biostimulant).

Finally, we analyzed and systematized the strategic motives and derived implications related to incumbent firms' challenges to incorporate biological solutions into their pipelines and portfolios. We analyzed these strategic motives through the lens of two main conceptual dimensions that were described in Section 2.

4 | Incumbents' Strategies to Introduce Biological Solutions

In this section, we present the main identified strategies of incumbents pursuing to explore biological solutions, which is the first research question in our paper. The main agrochemical and seed companies are the ones that have been more active in terms of engaging in biological solutions, outpacing companies in the fertilizer industry. Figure 3 presents a network chart that has the purpose of visualizing the full landscape of interactions among the incumbents and biological firms. The size of each circle represents the company's degree of centrality within the network, measured by the total number of interactions. Appendix S3 provides detailed information about the leading companies driving these interactions. As illustrated in the figure, the interaction landscape is predominantly dominated by firms in the agrochemical sector. The companies with the highest number of interactions are Bayer (15 interactions), Syngenta (13), Monsanto (9, all occurring before its acquisition by Bayer in 2018), and Corteva (8). These firms hold the most central positions in the network due to their combined crop protection and seed biotechnology capacities. This combination likely enhances complementarities between chemical and biological platforms, a topic explored further in the next section. A second group of agrochemical companies comes next with five recorded interactions each, including BASF, FMC, and UPL. Nutrien has been the most active company in the fertilizer sector, with three interactions. In terms of biological input companies (gray circles in the figure), the ones with the highest number of interactions include AgBiome (four interactions), Biophero, Pivot Bio, Novozymes,[8] and Bioceres[9] (three).

We have identified five different strategies incumbents are adopting to explore biological solutions. During the reading and coding stage, several codes were manually assigned to the press releases and news articles describing each interaction. Then, these codes were grouped into larger categories according to

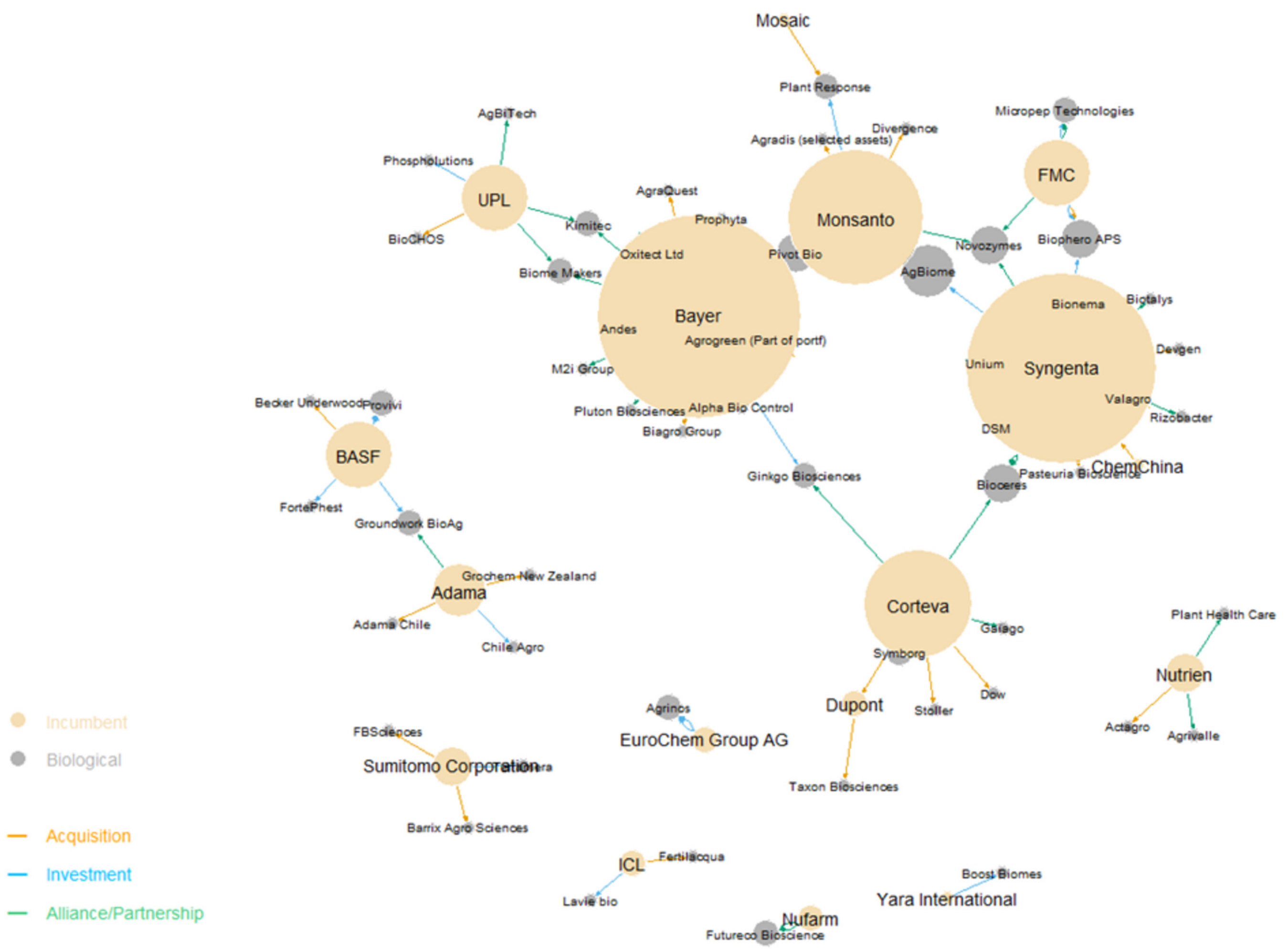

FIGURE 3 | Network of interaction between chemical ag input companies and biological firms. The bubble size represents the degree of centrality (measured by the number of interactions).

their common characteristics. These larger categories are the five main strategic purposes that characterize each of these interactions, which we define as follows:

- *Portfolio expansion*: In this case, the strategic purpose of the incumbent firm is to offer new biological solutions to their current clients or expand their own portfolio of biological products by looking for existing portfolios of smaller biological companies.
- *Marketing or distribution*: Similar to the previous one, the purpose here is to expand the offer of biological solutions but using third-party developments. In this case, this is done through the commercialization of specific products or brands in a region without significant technological development or portfolio acquisition compromises.
- *Technological platform complementarities*: The platform of one of the companies helps to accelerate the product development for the other. For the incumbent, this implies a combination of external knowledge with in-house development in which research capacities and facilities from both firms are involved. This requires the preliminary identification of complementary capabilities with the biological firms.
- *Product development*: R&D activities are involved, but not for the general purpose of accelerating technology deployment but rather to develop a specific product or solution.
- *Window of technology*: The incumbent interacts with a firm that does not yet have a product portfolio developed. Usually, there is no specific agreement or explicit purpose behind the investment. The strategic motivation is related to having the future priority of incorporating these technologies or solutions into their own portfolios.

Table 3 shows the codes that were the basis for building these five strategy categories and some extracts from the press releases for illustrative purposes. We include in Appendix S1 some examples of quotes that are the basis of the codes used in the inductive stage, which helps to describe how the coding process originally took place. Appendix S2 shows the detailed tree code, with colors per category, for easier visualization.

Figure 4 summarizes the strategic motives according to the type of deal.[10] Some incumbent firms use the acquisition of biological firms that already have a palette of products as a direct way of enhancing their portfolios. Acquiring existing firms (or part of their portfolios) is the most straightforward strategy for portfolio

TABLE 3 | Examples of strategic interactions.

Strategic motive	Main codes identified (inductive stage)[a]	Example extract from press releases
Portfolio expansion	"open new market segment"; "opening a new division"; "add to existing portfolio"; "position in biologicals"; "new product lines in biologicals"; "product portfolio complementarities"; "new biological solutions to current clients"; "existing portfolio of biologicals"	"The acquisition adds biologically produced state-of-the-art pheromone insect control technology to FMC's product portfolio and R&D pipeline, underscoring FMC's role as a leader in delivering innovative and sustainable crop protection solutions (...)"
Marketing or distribution	"specific region"; "exclusive distributor"; "marketing and distribution of specific solutions"; "specific focus in a product"	"Through the collaboration, UPL will distribute AgBiTech's entire portfolio of biosolutions through its Natural Plant Protection (NPP) business unit in the United States. AgBiTech is providing the technology and distribution rights throughout the United States for its entire portfolio (...)"
Technological platform complementarities	"enhance capabilities"; "complementary capabilities"; "create new competencies"; "merging r&d capabilities"; "acceleration of a product pipeline"; "develop new solutions"; "existing portfolio of biologicals"	"(...) This collaboration combines Corteva's deep knowledge of natural product discovery and agricultural expertise with Ginkgo's extensive cell engineering platform and DNA codebase to explore the next generation of naturally-inspired sustainable solutions (...)"
Product development	"joint development of specific products or solutions"; "specific focus in a product"; "develop new solutions"; "specific region"	"Pivot Bio and Monsanto Company, a member of the Bayer Group, announced today a collaboration entered into earlier this year to develop Bradyrhizobium strains with enhanced nitrogen production for U.S. soybean growers (...)"
Window of technology	"exploration"; "developing or in progress technology"; "novel technology"; "potential of a technology"; "challenge to develop a novel technology"	"(...) at Syngenta Ventures, we look for companies with great teams and a business focus that can make a step change in dramatically improving agriculture. AgBiome is exceptional on both fronts, but it also has a unique business model and structure that positions the company well for success (...)"

[a]See Appendix S1 for quotation examples of these particular codes.

expansion. Recently, we have seen large acquisitions by Corteva (Stoller and Symborg) and Syngenta (Valagro). Another motivation for acquiring existing companies is to add their core capabilities into their own research labs, looking for platform complementarities. While traditional crop protection companies have capacities in field testing, plant genetics, and crop varieties, biological companies know how to handle microbial strains and perform microorganism discovery. For example, BASF acquired Becker Underwood and Bayer acquired Agraquest, both in 2012.

A second way of interaction is through alliances, partnerships, or collaborations. This can be done, for example, by developing commercialization agreements in which the incumbent offers the biological firms' products through their own distribution channels, which implies fewer compromises regarding research facilities or funds. Companies developing biological solutions need this type of agreement to reach massive access to farmers. Examples of this are the agreements between Syngenta and Bioceres that allow Syngenta to distribute Rizobacter's seed treatment solutions, UPL and AgBiTech for the distribution of biosolutions in the United States, and Futureco Biosciences with Nufarm for the distribution of bioinsecticides first in Spain and later expanded to Belgium and the Netherlands. Another motivation for doing this is developing specific solutions or product lines. For example, Bayer and Pivot Bio agreed in 2018 to collaborate in developing nutrient fixation solutions based on Bradyrhizobium strains, or FMC and Microprep Technologies agreed to develop herbicides based on micropeptide technologies. Moreover, collaborations or agreements can also be a source of technological platform sharing. This approach implies a combination of the acquisition of external capacities with in-house development. The agreements going in this direction are the ones by Corteva and Gingko for the use of synthetic biology to accelerate the microbial discovery process or UPL and Bayer with Kimitec, for the leverage through their artificial intelligence platform (LINNA).

Finally, we see corporate venture capital investments mainly related to the possibility of accessing future technological development. In many cases, incumbents identify a company with a technology that is still under development but has a promising future. These companies may not yet have a fully market-ready product palette, but it is in the interest of the incumbents the possibility of having priority toward those technologies in the future. For example, BASF Venture Capital was an active investor in series B and C of Provivi, a company producing pesticides based on insect pheromones, and Groundwork BioAg, an Israeli start-up producing mycorrhizal inoculants. In this line, FMC invested in Biophero APS, another company exploring pheromone-based solutions. In

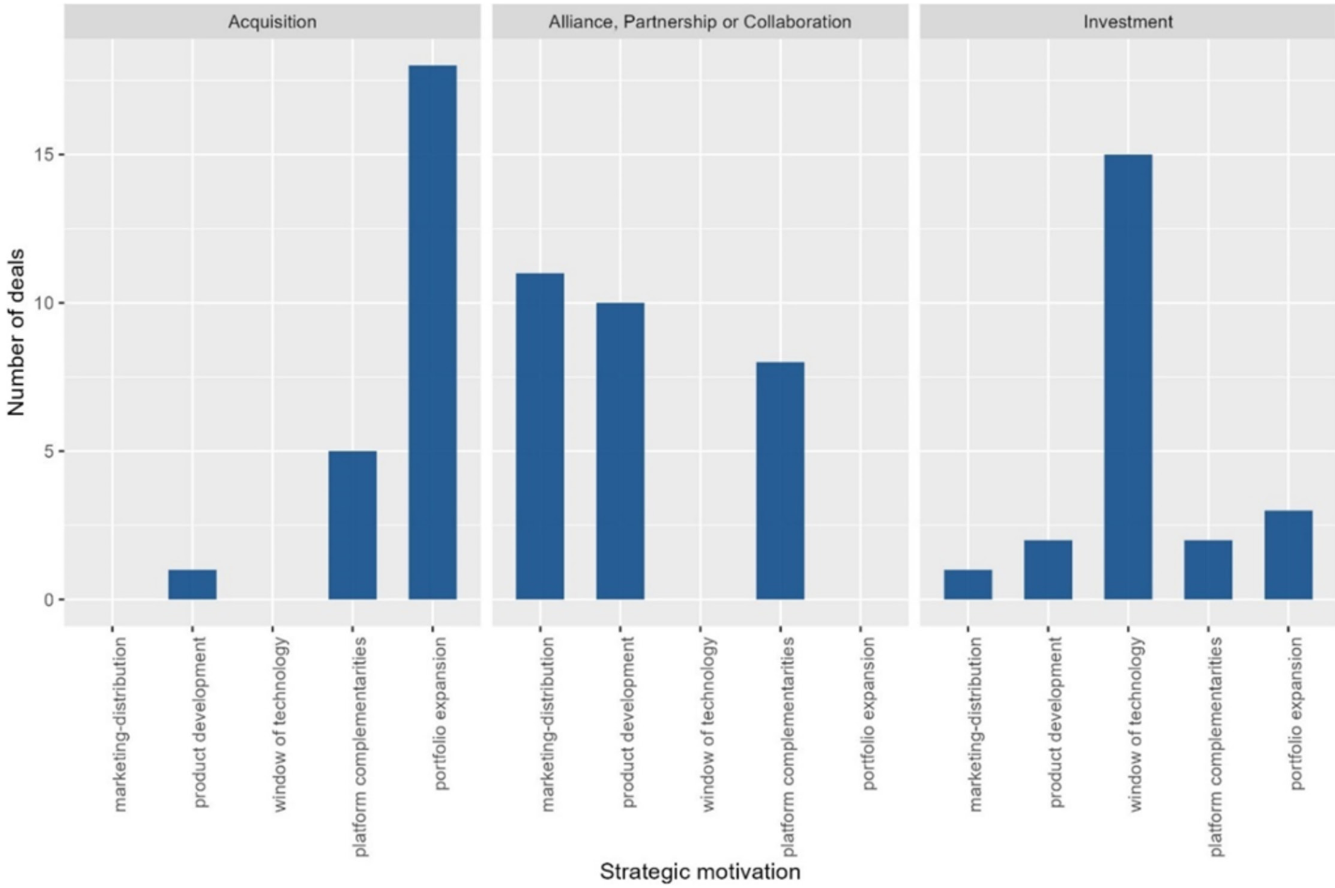

FIGURE 4 | Summary of the strategic motivations behind the interaction of incumbent and biological firms.

some other cases, the incumbent firm makes this investment to exploit technological complementarities. For the incumbent firm, this is a way of accelerating the internal development of biological solutions, which was the original motivation for Bayer's investment in Joyn Bio, a joint venture with the company Gingko.

The modes of interactions described in this section reflect how incumbents are partially "outsourcing" their R&D process in the development of biological solutions. This is related to three aspects. First, smaller firms are often more dynamic in their innovation rates and the introduction of novel solutions (Jensen et al. 2020), allowing larger firms to capitalize on existing technological advancements and products (Hockerts and Wüstenhagen 2010). Second, incumbent firms benefit from external knowledge by innovating in an open environment, fostering a coevolutionary relationship with smaller, promising firms (Dushnitsky and Lenox 2005; Powell and Grodal 2005). Finally, incumbents can adopt a more offensive approach (A. Afuah 2003) by investing in, forming alliances with, or acquiring companies developing emerging technologies—such as in the case of biological solutions. This allows them to shape their competitive environment by influencing the types of technologies that enter the market and the pace of innovation, thereby strengthening their competitive position (Béné 2022). At the same time, these strategic interactions enable start-ups and small-to-medium–sized firms to accelerate their product development, enhance technological performance, and gain market access (Baum et al. 2000).

As part of a complementary analysis, we examined additional interactions involving smaller companies in the chemical crop protection and synthetic fertilizers industries that fall outside the C8 group included in our main analysis. A detailed list of these agreements (28 in total) and their classification is provided in Appendix S4. While these companies do not strictly qualify as incumbents under our core definition, their strategic patterns provide additional comparative evidence of how know-how and capacity constraints emerge across different organizational scales. Our findings indicate that the strategic motivations identified in the primary analysis also apply to this broader group of firms not part of the C8 group. Compared to larger firms, these smaller companies primarily engage in alliances, partnerships, and collaboration agreements, while acquisitions and investments are less common—likely due to the greater financial demands of such activities. Additionally, strategies focused on direct portfolio expansion are less prevalent among smaller firms than they are among larger incumbents. Instead, these firms tend to prioritize agreements focused on product development, securing exclusive distribution rights for specific solutions, and leveraging technological complementarities.

5 | Incumbent Firms Facing the Challenges Posed by Biological Solutions

In this section, we delve into the second research question of the paper, related to the underlying technical and commercial challenges of introducing biological inputs on a large scale. The strategies identified in the previous section respond to several challenges that incumbents need to overcome to incorporate biological solutions in their product portfolios and research pipelines. We will characterize each strategy we obtained from our data in light of those challenges, building on the two-dimensional framework described in Section 2. The first relevant dimension for this analysis is the scope of the strategic commitment that the company is making at a corporate level. When there is high strategic commitment, the company either makes substantial investments, adapts its corporate strategy, or compromises research time and efforts. Here, the potential value capture is high, but so are the risks undertaken. The second dimension is related to the market readiness of the solution involved. Sometimes, a company may seek a long-term exploration process, developing or acquiring solutions that need time to become commercially available. In other cases, a firm may require a quicker and more direct process for exploring new technology that builds on current capacities and takes them rapidly to the market (i.e., accessing an already developed palette of products or an advanced research pipeline to enter the final deregulation stage, which implies technological exploration but also leveraging its current business units).

We classify the five strategic motives in terms of the two dimensions (see Figure 5), and we describe each of them considering the challenges that the biological industry poses for incumbent input companies. The purpose of this analysis is not to circumscribe each incumbent to one single strategic motivation (i.e., Company A uses portfolio expansion, Company B uses product development, etc.) but rather to understand the reasons that drive these dominant firms into biological solutions, acknowledging that several strategic pathways exist for this purpose.

In the strategy we defined as portfolio expansion, the incumbent normally acquires a biological firm with an existing palette of products that can be quickly added to their portfolio. This requires a high strategic commitment, both in terms of the funds needed for acquisition and in terms of making the necessary arrangements at the corporate level to integrate external resources into the structure. This commitment implies taking products already in the markets ("high readiness"), in which the

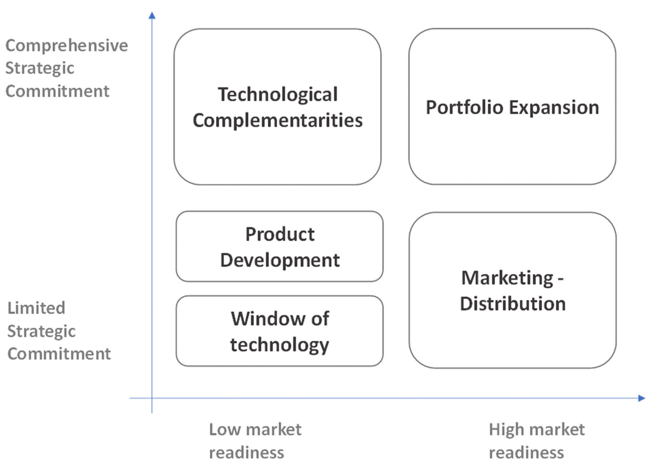

FIGURE 5 | The strategic motivations behind the interaction of incumbent and biological firms: a two-dimensional perspective.

development of internal capabilities is moderate to low (at least in the short term). This strategy is a concrete response to the need to show results quickly in terms of the biological products offered in the palette. Incumbent firms face substantial pressure from shareholders to show visible sustainability commitments (Eccles and Klimenko 2019; Ghosh and Crifo 2023). Moreover, their current clients (i.e., farmers) start hearing about these solutions in their farmer networks, and this may motivate the desire to adopt or at least try part of these solutions (Burlig and Stevens 2023; Kreft et al. 2023). The acquisition of already developed products (most likely with existing salesforce capabilities) allows incumbent firms to respond quickly to these demands. This also reflects the challenges faced by the traditional agricultural input industry in developing new molecules for crop protection and novel synthetic products for plant nutrition (Dickson et al. 2019). The introduction of biological products has been notably more dynamic compared to chemical products (Phillips McDougall 2019), so this trend offers incumbent companies an expedient pathway to boost their sales. This process requires organizational ambidexterity, in the sense that while the company is exploring a technological alternative, it needs to leverage its current product palette to exploit complementarities as quickly as possible.

Unlike portfolio expansion, a marketing or distribution agreement for a specific area involves substantially lower strategic commitment (i.e., no money is involved in purchasing another company, and there is no need to adapt the company structure). Still, it keeps the logic of a quick response to the demand of offering biological products. At the same time, for the biologicals firm, this is an opportunity to access the incumbent's distribution channels while keeping control of the company. One of the main challenges for biological firms is to develop distribution channels and reach farmers directly. This is also reinforced by the fact that farmers continue to favor traditional brands when purchasing biological solutions. According to CropLife Biologicals Survey (Sfiligoj 2024), industry leaders such as BASF, Corteva, and Bayer remain the top choices for farmers when acquiring biological products, underscoring the strategic logic of small companies in leveraging the distribution channels of incumbent firms. On the long run, agricultural input suppliers play a key role in technology adoption (Dar et al. 2024) and will be central actors in the development of biological markets. In the case of exclusive suppliers, incumbent input companies should work closely with them to build new technical capacities. Independent distributors need to train their salespeople to adapt to the current changes and understand the particularities of these products.

As opposed to the high market readiness reached by portfolio acquisition or marketing agreements, the exploration of technological platform complementarities with biological companies implies a path of development in which incumbent firms seek to develop internal capabilities from the beginning. As expected, this requires time to see a payoff in terms of commercially available products. Incumbent firms thrive at developing standardized and large-scale solutions but have to build internal skills to develop biological inputs, which are less standardized and require a more tailored process. All their R&D capabilities in the last 30–40 years have been built around the concept of massive products and solutions that can be scalable

(Clapp 2021a; Howard 2015). In this context, the strategic actions of incumbent firms may mirror processes observed in the biotech pharmaceutical industry, in which major pharmaceutical companies often establish agreements with R&D firms to jointly develop solutions or acquire licenses for technologies that are subsequently integrated into their technological platforms (AgriThority 2023).

Compared to traditional synthetic fertilizers and chemical inputs, which are generic and scalable solutions, biological products need to be tailored to specific geographies, crops, soil types, and weather conditions. For example, a broad-spectrum fungicide (e.g., azoxystrobin) is a standardized product designed to deliver results in different crops and climate conditions. In contrast, equivalent biocontrol solutions may be applied in the same field at a similar time of the year and show variable results between two agricultural cycles (O'Connor 2022). The in-house development of biological solutions requires tools that leverage their own capabilities and favor adaptation. At the same time, incumbent firms need to calibrate biological technologies in terms of their own absorptive capacity because complementarities do not necessarily emerge straightforwardly (Carmona-Lavado et al. 2021).

Finally, agreements or investments for developing specific products or solutions in companies that provide a window of technology do not require significant strategic commitments and do not provide market-ready products. These strategies involve internal resources and building research capabilities with a more circumscribed strategic commitment (i.e., the incumbent does not necessarily compromise their full research capabilities but only circumscribe to a specific project). This type of low-commitment strategy contributes to building capacities in the long run without assuming unbearable risks. This approach is grounded in the fact that biological solutions typically have a narrow target range and incumbent firms capitalize on this by leveraging such agreements to develop biocontrol products tailored to specific pathologies or biofertilizers designed for particular functionalities (Pandita et al. 2024). Overall, this is a response to the typical innovator dilemma (Christensen 1997) that incumbents are facing with these new products: Engaging deeply and quickly in these new technologies outside their main core competencies may look attractive (especially in terms of market perspectives) but holds the risks of entering into uncharted waters and leading to failure. While it is unclear now whether biological solutions will become an efficient and less expensive solution that will potentially become a new standard, incumbents want to mitigate vulnerability in front of a potential technological disruption, so they set foot in this technology without the need for compromising a substantial share of their current technological and market focus.

Thus, the emergence of biological solutions drives agricultural incumbents into a somehow uncharted territory, where it is not clear to what extent they should bet money, time, and capabilities on developing these new types of solutions. The process by which incumbent firms reassess their competitive business strategies in response to new technological developments is not new. The pharmaceutical industry provides a classic example. In this sector, large pharmaceutical companies have strategically interacted with biotechnology firms possessing specialized knowledge to accelerate R&D processes (Orsenigo et al. 2006). A comparable dynamic occurred in vaccine development, as demonstrated during the COVID-19 pandemic, where major pharma companies collaborated with R&D firms to accelerate the mRNA platform (Gaviria and Kilic 2021). Similarly, the evolution of the seed industry over the past 30 years has seen large chemical companies enter the seed technology sector. These firms initially explored and subsequently acquired smaller biotech companies to leverage complementarities between seed technology and crop protection chemicals (Clapp 2021a; Deconinck 2020). Current evidence indicates similar processes of strategic interactions. The COVID-19 pandemic accelerated digitalization in food retail, prompting global retailers to develop pivoting strategies by acquiring, investing in, or partnering with companies specializing in e-commerce (Reardon et al. 2021). A comparable trend is observable in front of the rapid digitalization of agriculture (usually known as agriculture 4.0). Through strategic interactions with smaller firms, large ag machinery dominant firms have increasingly integrated digital technologies, transitioning from a product-centric focus to one emphasizing services and platform solutions (Birner et al. 2021; Sauvagerd et al. 2024).

The productive and technological logic of biological products does not completely fit agricultural input incumbents, whose know-how and expertise have been developed for a different purpose. Then, compromising excessive knowledge or asses could potentially lead to failure. As we previously mentioned in Section 3, despite the optimism that companies may express in the press releases, which is related to attracting investors and persuading shareholders, the final result of the interaction may show different degrees of success. Our findings are consistent with previous studies showing that companies tend to combine several strategies to access new technology, pursuing a balanced portfolio of strategies, depending on the type of technical and market uncertainty, the proximity with the technological development of the partner, or the type of strategic alignment with other firms (Ortiz-Gallardo et al. 2013; van de Vrande 2013; van de Vrande et al. 2009). The selection of an appropriate strategy in each case will depend on the specific technology involved. It may be reasonable to adopt a window of technology approach for less mature technologies before pursuing product development or acquisition pathways. The required speed of implementation also influences strategic choices: While a company explores certain technologies through strategies demanding minimal organizational commitment, it can simultaneously advance other initiatives with greater market readiness. Indeed, the five strategic lines likely coexist at the heart of the corporate strategies of the most active companies in the exploration of biological solutions and confirm that incumbents tend to combine several approaches when pursuing the exploration of new technology (Rothaermel and Deeds 2004; Stettner and Lavie 2014).

On the other hand, for start-ups and science-based SMEs developing biological inputs, it is important to acknowledge that, in spite of their technical know-how, significant resource asymmetries in comparison to incumbents lead to challenges for market entry and growth. While these smaller firms often possess cutting-edge scientific expertise, they face disadvantages in terms of financial resources, considering that conducting lab research and extensive field trials demands significant funds (Mac

Clay and Sellare 2025). Even if a small company overcomes these stages, there are high capital requirements for taking production facilities onto a commercial scale. Moreover, regulatory compliance capabilities (often critical in agricultural biotechnology) to deal with complex and diverse regulatory approval processes across different jurisdictions constitute additional barriers (da Silva Medina et al. 2023). Finally, incumbent firms have established marketing infrastructure and distribution channels to reach farmers in different regions and countries, which is usually complex to develop from scratch for a start-up or a small firm. These resource asymmetries fundamentally shape smaller firms' strategic preferences, often leading to alliances or other collaborative approaches with incumbents. Securing access to funds via (corporate) venture capital provides the financial runway needed for initial research, but establishing strategic agreements with companies that have already developed robust production facilities and distribution channels offers a pragmatic pathway to overcome scale disadvantages. Incumbent firms may profit from developed market capabilities, including established brands, complementary assets, and distribution channels (A. N. Afuah and Prakah Asante 2015), which are unlikely to be developed exclusively by a small firm despite its technical knowledge in biological solutions.

6 | Conclusion

Biological products are gaining recognition as promising components of a shift toward more sustainable agricultural systems. This shift is driven by growing pressures to reduce reliance on synthetic fertilizers and agrochemicals and the increasing prevalence of insect and weed resistances that undermine the efficacy of traditional chemical solutions. While extensive research has explored the technical dimensions of biological solutions, this paper has introduced a novel perspective by examining the industrial dynamics prompted by the emergence of biological inputs. We have shown that large multinational agribusiness firms are pivoting their strategies to incorporate biological solutions in different stages of development. This behavior may prove critical in shaping the technological and market trajectories of these products, particularly in a sector characterized by high industrial concentration.

The rise of biological products presents significant commercial and technical challenges for established players in the agricultural input sector. In the technical sphere, the rationale for using living organisms is less standardized and more variable than traditional chemical products. While the efforts of the agricultural input industry in the last 30 years have focused on providing large-scale standardized products (e.g., glyphosate, dicamba, azoxystrobin, and nitrogen or phosphorus fertilizers), biological products create new challenges in the discovery process and require different R&D skills. Consequently, the commercialization aspects are also different: Incumbent firms need to train their sales forces to approach farmers differently and raise awareness about these products. In this paper, we described and systematized the current landscape of interactions between incumbent aginput firms and biological firms. We have identified five strategies incumbents pursue to incorporate biological solutions into their product palettes and research pipelines: portfolio expansion, marketing and distribution of solutions, technological platform complementarities, product development, and exploration of technological windows of opportunity.

Our analysis has several policy and business implications. Policymakers promoting the transition to sustainable agricultural practices, in which biological inputs can play a critical role, must address three key challenges. First, the integration of biological solutions by incumbent firms suggests that biological inputs will complement rather than replace chemicals (Goulet and Hubert 2020). We will likely experience the coexistence of biological and traditional chemical inputs. This is confirmed by the farmers' views around these products, which perceive them as complementary to traditional products rather than a solution to be applied exclusively, understanding that the combined approaches give the highest yield performance (McKinsey & Company 2024). Thus, extension programs and training initiatives—potentially developed with industry partners and distribution networks—are essential in helping farmers overcome the technical complexities of biological inputs, including application schedules, equipment compatibility, and system integration. Second, the entry of agricultural input incumbents into the biological market signals that wider adoption may not automatically reduce concentration in the agricultural input industry. Industrial policies must create space for smaller, local firms to compete effectively, avoiding a market consolidation pattern like the one in seed biotechnology (Deconinck 2019). Finally, policy frameworks can drive innovation in biological inputs by harmonizing cross-border regulations and reducing compliance costs, particularly benefiting small- and medium-sized firms.

From a business perspective, our study shows that incumbent input firms are facing a transition that may challenge their business-as-usual scenario. These companies are exploring to find the right balance between their core business and these new products based on living organisms and natural extracts. As was described in this paper, biological products are less standardized than traditional synthetic fertilizers and chemical inputs. While internal R&D could focus on exploitation for developing new seed, crop protection, and nutrition alternatives, the use of investments, acquisitions, and strategic alliances will help enhance their portfolios in the biological segments as part of a technological exploration strategy. At the same time, these companies are looking for complementarities in their portfolio, which may imply a change in the process of value capture, from selling products (i.e., seeds and agrochemicals) to selling bundled solutions that combine genetic technology, chemical and biological combined input packages, and data analysis.

This paper offers critical insights into the strategies employed by agricultural input incumbents in response to the emerging wave of biological solutions, including biofertilization, biostimulation, and biocontrol. By systematically analyzing the interactions between large multinational corporations and companies specializing in biological solutions, we contribute to both innovation management and industrial organization literature within the context of rapid technological change aimed at enhancing the sustainability of global agri-food systems. Future research should integrate technological innovation, industrial organization, and strategic management fields to address emerging trends in the biological solutions industry. Advanced algorithms can streamline microorganism identification and reduce the time and costs of developing biological solutions, positioning AI-driven firms as pivotal players in the industry dynamics. Similarly, collaboration among developers, distribution networks, and rural extension agents is essential for designing products that promote farmer adoption, highlighting the relevance of integrating technology adoption literature in the future. Finally, precise gene-editing technologies, such as CRISPR-Cas, could accelerate the discovery and development of microorganisms with targeted functional traits, offering a competitive advantage to companies leveraging these tools. These developments provide fertile ground for exploring the evolving complexities and structural shifts in the agricultural inputs industry.

Endnotes

[1] The terms "biological inputs," "biological solutions," and "biological products" are used synonymously throughout the text and express the same concept.

[2] Fertilizers are a commodity-like product, so this market has historically shown lower concentration rates compared to the seed and crop protection one.

[3] According to their website, their focus is on consumer and retail, tech, insurance, healthcare, industrial, and financials.

[4] Crunchbase is probably the exception (offering a suitable open-access research-oriented alternative), so it was therefore used as a complementary source in our study, as it is explained in this section.

[5] Not every website has the same criteria in terms of how the search engine is designed, as it may happen, for example, in academic databases. This required flexibility regarding the query approach and criteria to retrieve information and build the database or interactions.

[6] During the search process, we also identified 12 additional interactions for smaller companies that are not among the top sellers (i.e., Helm, Bioceres, and American Vanguard). These are not formally accounted in the database, but we reviewed them as complementary information for the coding stage in Atlas.ti.

[7] Atlas.ti 9 9.1.7.0. 2020 Atlas.ti Scientific Software Development GmbHx.

[8] Novozymes' scope of operations extends beyond agricultural solutions, including industrial applications (i.e., industrial enzymes) and biopharma. However, the company's expertise in biosolutions has driven its entry into the biological segments within the agricultural sector over the past decade.

[9] It is a seed technology company that expanded into the biological segment following its acquisition of Rizobacter in 2016.

[10] The figure is presented in number of deals because the value of those deals (in particular, acquisitions or corporate venture investments) is not usually disclosed in press releases.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.