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The agronomics of bio-inputs: Evidence from soybean production in Brazil

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ABSTRACT

Technological advancements in agricultural bio-inputs already offer sustainable alternatives to complement or replace chemical inputs in certain agricultural practices. This study presents the bio-inputs commercially available in Brazil, a leading country in this sector globally, and their adoption by soybean farmers, the main agricultural commodity produced in Brazil. The biological alternatives available on the market were summarized based on the directions for use available on the product labels and interviews with representatives of the private companies marketing the products. The adoption of biologicals was estimated based on a survey conducted with marketing representatives in 8 agricultural regions across Brazil. The study characterized the portfolio of biological solutions currently available for soybean production, providing the agronomic positioning of inoculants, biofungicides, bioinsecticides, and bionematicides. Some biological products are positioned as replacements for chemicals, as in the case of nematicides or fungicides in initial applications under conditions of low pressure. Biologicals are also used in a complementary way with chemicals, as in the case of insecticides, bringing the benefit of increased effectiveness in pest control and reduced resistance to chemicals. Adoption levels vary across product categories and according to the technological levels of farming systems and regions. This study provides one of the first comprehensive assessments of the agronomics of bio-inputs and offers insights into technological transitions toward more sustainable agriculture. It is expected to help agricultural science professionals, students, and farmers gain a better understanding of bio-input applications in crop protection and plant growth.

Contribution/Originality: This study provides one of the first comprehensive analyses of Brazil's agricultural bio-inputs sector by revealing farmers' adoption of inoculants, biofungicides, bioinsecticides, and bionematicides in soybean production. It shows that bio-inputs can complement and, in certain cases, replace agrochemicals, advancing understanding of potential sustainable technological transitions.

1. INTRODUCTION

Agriculture faces the challenge of simultaneously increasing food production while reducing its dependence on synthetic fertilizers and pesticides, mitigating environmental impacts, and improving resilience to climate change. These challenges have intensified interest in agricultural bio-inputs, which comprise products derived from microorganisms, macroorganisms, plant extracts, enzymes, and other biological resources capable of promoting plant growth, improving nutrient availability, and controlling pests and diseases. Bio-inputs are increasingly recognized as important components of sustainable intensification strategies and regenerative agriculture because they can enhance crop productivity while reducing the environmental externalities associated with conventional agricultural inputs.

Recent advances in microbiology, biotechnology, and formulation technologies have substantially expanded the range and effectiveness of commercial biological products. Modern bio-inputs are no longer restricted to biological nitrogen fixation but include microbial inoculants, nutrient solubilizers, biofungicides, bioinsecticides, bionematicides, and emerging technologies based on microbial consortia and bioactive metabolites. Improvements in microbial strain selection, formulation stability, shelf life, and compatibility with conventional crop protection products have accelerated the commercialization and adoption of biological solutions worldwide.

Brazil has become one of the world's leading markets for agricultural bio-inputs due to the combination of large-scale tropical agriculture, a dynamic biotechnology sector, and a regulatory environment that has encouraged innovation. In recent years, the Brazilian bio-input market has grown considerably faster than the global average, driven mainly by soybean, corn, and sugarcane production systems. Brazil already has biological solutions for various farming practices, with adoption rates ranging from 41.7% for biosolubilizers to 88.9% for biological control of nematodes by soybean farmers in more technologically advanced regions [1].

Soybean production represents the largest market for agricultural bio-inputs in Brazil. The crop has historically demonstrated the successful replacement of synthetic nitrogen fertilizers through biological nitrogen fixation with *Bradyrhizobium* spp., one of the most successful examples of microbial technology adoption in world agriculture. More recently, biological alternatives have expanded to disease, insect, and nematode management [1]. Brazilian farmers are global leaders in bio-nutrients and bio-controls, helping the bio-input sector grow by 15% annually. In 2025, its market value reached 1 billion Euro; however, still far below agrochemicals at about 15.8 billion Euro [2]. Soybeans account for 62% of the total bio-input market in Brazil, as it is the main agricultural commodity produced in the country.

In most cases, biological products are adopted alongside the continued use of synthetic inputs, in some cases reducing the frequency or dosage of chemical applications. Besides inoculants, bionematicides emerge as the main biological tools used as substitutes for synthetic nematicides in preventive treatments, whereas biological herbicides are not yet available on the market [3].

Despite the rapid expansion of the sector, there is still limited understanding of how commercial biological products are actually positioned within modern production systems. Most scientific studies evaluate the efficacy of individual microorganisms or specific commercial products under experimental conditions, whereas considerably less attention has been devoted to understanding how biological technologies are recommended by manufacturers, incorporated into agronomic management, and integrated with chemical technologies in commercial farming. Likewise, comprehensive descriptions of the biological solutions currently available for soybean production remain scarce, particularly regarding their mechanisms of action, application strategies, technological innovations, and potential roles as substitutes for or complements to synthetic inputs.

This knowledge gap is particularly relevant because the contribution of bio-inputs to sustainable agriculture depends not only on their biological efficacy but also on their practical integration into crop management systems [4]. Commercial recommendations increasingly emphasize the complementary use of biological and chemical products rather than complete substitution, reflecting a transition toward integrated technological packages that combine different mechanisms of action to improve productivity, reduce production risks, and delay the evolution of resistance.

This study addresses this gap by providing a comprehensive assessment of the current agronomics of commercial agricultural bio-inputs used in soybean production in Brazil. Specifically, the study aims to: (i) characterize the portfolio of biological solutions currently available for soybean production; (ii) analyze the agronomic positioning of these technologies, including their potential as substitutes for or complements to chemical inputs; and (iii) estimate the adoption of the main categories of agricultural bio-inputs among Brazilian soybean farmers. By integrating information from commercial products, scientific evidence, and adoption patterns, the study provides an updated overview of the state of the art of biological technologies in one of the world's largest agricultural markets and contributes to understanding how bio-inputs are reshaping crop management toward more sustainable production systems.

2. METHODOLOGY

This study adopted a mixed-methods approach combining documentary analysis, expert interviews, literature review, and a nationwide survey of commercial representatives to characterize the current agronomic positioning of agricultural bio-inputs for soybean production in Brazil.

2.1. Portfolio of Commercial Biological Solutions

The portfolio of commercial biological products was constructed through a systematic review of labels and technical recommendations for leading bio-inputs registered in Brazil. Product labels were examined to identify target pests and diseases, active microorganisms, mechanisms of action, application methods, registered targets, formulation technologies, and recommendations on combined or alternative use with chemical inputs.

The documentary analysis was complemented by semi-structured interviews with technical and commercial representatives from the companies responsible for marketing these products. The interviews aimed to clarify the agronomic positioning adopted by each manufacturer, including whether products were recommended as substitutes for synthetic inputs or as complementary technologies within integrated crop management. Information obtained during the interviews was cross-checked against official product labels to ensure consistency.

2.2. Review of Scientific Evidence

To compare commercial positioning with scientific knowledge, a literature review was conducted focusing on studies evaluating the efficacy of the microorganisms and commercial products identified in the market survey. Peer-reviewed publications, technical reports, and independent evaluations were reviewed to summarize evidence regarding biological control efficacy, plant growth promotion, and comparisons with conventional chemical products. The objective was not to conduct a formal meta-analysis, but rather to provide an updated overview of the scientific evidence supporting the main technologies currently available to farmers.

2.3. Analysis of Agronomic Positioning

The agronomic positioning of biological products was analyzed by comparing the recommendations contained in product labels and the information obtained during the interviews. Products were classified according to their intended agronomic function, including biological nitrogen fixation, plant growth promotion, nutrient solubilization, disease control, insect control, and nematode management. Special attention was given to the relationship between biological and chemical technologies. Products were categorized according to three management strategies: (i) complete substitution of chemical inputs, when biological products were positioned as alternatives to synthetic products under certain conditions; (ii) complementary use or technology stacking, when biologicals were recommended in combination with chemicals; and (iii) conventional biological management practices, such as soybean inoculation with nitrogen-fixing bacteria, which already constitute standard agricultural practice.

2.4. Survey on Farmers' Adoption

The adoption of agricultural bio-inputs was estimated through a survey with commercial representatives operating in eight soybean-producing agricultural regions across Brazil. Commercial representatives were selected because of their direct technical assistance to farmers and their broad knowledge of regional adoption patterns.

Respondents were asked to estimate the proportion of soybean farmers using eight categories of biological products: foliar biofungicides, soil biofungicides, bionematicides, fungal bioinsecticides, viral bioinsecticides, *Bacillus thuringiensis* (Bt)-based bioinsecticides, inoculants, and nutrient-solubilizing microorganisms.

The results should be interpreted as expert assessments reflecting commercial experience across the main soybean-producing regions rather than precise measurements of national adoption rates. Nevertheless, because the interviewed representatives collectively covered the principal soybean-producing areas in Brazil, the survey provides a comprehensive overview of current adoption patterns.

3. RESULTS

3.1. Portfolio of Biological Solutions

This section presents a portfolio of potential biological solutions focusing on soybean cultivation. Biological products are available for the main diseases and pests, with registrations by target. It presents the biological solutions available on the market for inoculation and biological control, mainly of soil and foliar fungal diseases, as well as pests such as insects and nematodes (Table 1). The following sections detail each category of solutions, ranging from inoculants to nematicides.

Table 1. Portfolio of biological products for soybean cultivation in Brazil.

Inoculants					
Main Functions	**Chemical Alternatives**	**Biological Products**	**Mechanisms of Action**	**Application Method**	**Biological/Chemical**
• Nitrogen fixers	• Nitrogen mineral fertilisation - poorly viable due to the high demand for N in the crop	• *Bradyrhizobium japonicum* and *Bradyrhizobium elkanii*	• Atmospheric nitrogen fixation via the nitrogenase enzyme	• Seed treatment or sowing furrow	• Allows total replacement of N fertilisation in soybeans
		• *Methylobacterium symbioticum**	• Foliar nitrogen fixation	• Foliar, at stages V6 to R1	• Complements biological nitrogen fixation and supplies N
• Growth promoters	• Synthetic hormones	• *Azospirillum brasilense*	• Root growth promotion: production of phytohormones (e.g., auxins), increasing soil exploration	• Seed treatment or sowing furrow	• Co-inoculation technology for root hair promotion and early nodulation
• Nutrient solubilisers (mainly phosphorus and, less commonly, potassium)	• Phosphate fertilisation	• Products based on microorganisms such as *Bacillus megaterium*, *B. subtilis* and *Pseudomonas fluorescens*	• Secretion of organic acids that form stable complexes with Fe^{3+}, Al^{3+} and Ca^{2+}, releasing the P; production of enzymes that mineralise P	• Seed treatment or sowing furrow	• In addition to mineral fertilisation to improve nutrient availability to the plant
*Although registered in Brazil, there is no scientific consensus regarding the efficacy of *Methylobacterium symbioticum* as a nitrogen fixer (see Giller, et al. [21]).					
Soil Fungicide					
Main Targets	Chemical Control	Biological Control	Mechanisms of Action	Application Method	Biological/Chemical
• White mould (*Sclerotinia sclerotiorum*) • Rhizoctonia (*Rhizoctonia solani*) • Fusarium wilt (*Fusarium solani*) • Root rot (*Phytophthora sojae*) • Charcoal rot (*Macrophomina faseolina*)	•Benzimidazoles • Carboxamides • Strobilurins • Fluazinam • Triazoles	Fungus-based products: • Mainly *Trichoderma* Bacteria-based products: • Mainly *Bacillus*	Products based on *Trichoderma*: • Parasitism • Competition • Antibiosis Products based on *Bacillus*: • Biofilm • Resistance induction • Antibiosis	• Seed treatment (ST and IST) • Furrow and boom spray	• It is possible to combine the biological product with the chemical product already used, provided they are compatible
Foliar Fungicide					
Main Targets	Chemical Control	Biological Control	Mechanisms of Action	Application Method	Biological/Chemical
• Asian soybean rust (*Phakopsora pachyrhizi*) • Target spot (*Corynespora cassiicola*)	• Multi-site: Mancozeb or chlorothalonil; Copper-based • Specific-site: Triazole, Strobilurin,	• Products mainly based on *Bacillus* species and/or their metabolites:	Products based on *Bacillus*: • Biofilm • Resistance induction	• Application 0 (V3) - Biological only • V5 - Biological + specific-site • R1 - Biological + specific-	• According to the product and inoculum pressure: • Biological can replace multi-site • Biological can replace specific-

• Powdery mildew (*Microsphaera diffusa*) • Cercospora leaf blight (*Cercospora kikuchii*) • Anthracnose (*Colletotrichum truncatum*) • Bacterial blight (*Pseudomonas syringae*)	Carboxamide • Chemical control is carried out preventively with multi-site and specific-site fungicides, respecting the phenological stage, inoculum pressure and resistance management	• *Bacillus velezensis* • *Bacillus pumilus* • *Bacillus amyloliquefaciens* • *Bacillus subtilis*	• Antibiosis • Competition for space and nutrients	site • Other applications - chemical multi-site + specific-site • Most companies position biologicals as replacements for multi-site chemicals in the vegetative phase, although management strategies vary	site • Combined use
Insecticide					
Main Targets	Chemical Control	Biological Control	Mechanisms of Action	Application Method	Biological/Chemical
• Soybean looper (*Chrysodeixis includens*) • Fall armyworm (*Spodoptera* sp.) • Darker-spotted leafworm (*Spodoptera eridania*) • Helicoverpa (*Helicoverpa armigera*) • Whitefly (*Bemisia tabaci*) • Brown burrowing bug (*Scaptocoris castanea*) • Neotropical brown stink bug (*Euschistus heros*) • Spotted spider mite (*Tetranychus urticae*) • Thrips (*Frankliniella schultzei*)	• Benzoates • Carbamates • Diamides • Pyrethroids • Organophosphates • Neonicotinoids • Growth regulators	• Bacteria: *Bacillus thuringiensis (Bt); Pseudomonas fluorescens* • Viruses: Baculovirus • Fungi: *Beauveria bassiana; Metarhizium anisopliae; Metarhizium rileyi; Isaria fumosorosea; Isaria javanica* • Macroorganisms: - Predators: *Chrysoperla externa; Amblyseius tamatavensis* - Parasitoids: *Telenomus podisi; Trichogramma pretiosum*	• Bt needs to be ingested by caterpillars when they feed on leaves, affecting their gut and leading to death • Baculoviruses are specific to the target pest. It must be ingested by the caterpillar. It takes about 16 hours to start affecting the insects • Fungus needs to come into contact with the pest to colonise its body. It takes about 3 to 5 days to reduce the insect population • Macroorganisms act through predation or egg parasitism. *Telenomus* parasitises stink bugs; *Trichogramma* parasitises caterpillars	• Bt, fungi and viruses are used based on pest monitoring in the soybean crop. Preferably at the beginning of the insect's development and, for Bt and viruses, up to the third instar of the caterpillar. • Macrobiologicals are applied preventively or at the beginning of the infestation, via manual release with cards, drones or aircraft	• Bioinsecticides are applied together with compatible chemical insecticides, as they act by colonising the insects and multiplying in the environment, prolonging residual control, whilst chemicals rapidly decrease the pest population
Note: Products based on Bt and viruses are used in caterpillar control. Fungus-based products are used to control whiteflies, stink bugs, mites and thrips. Macroorganisms parasitise and prey on caterpillar eggs and also control other insects.					
Nematicide					
Main Targets	Chemical Control	Biological Control	Mechanisms of Action	Application Method	Biological/Chemical

• Root-knot nematode (*Meloidogyne javanica* and *Meloidogyne incognita*) • Soybean cyst nematode (*Heterodera glycines*) • Root lesion nematode (*Pratylenchus brachyurus*) • Reniform nematode (*Rotylenchulus reniformis*)	• Chemical nematicides are classified according to three main mechanisms of action based on the chemical group: • Avermectins, Carbamates and Organophosphates act on the nervous system, causing paralysis and death of the nematodes • Pyridinyl-ethyl benzamides and Phenylpyridinamides inhibit cellular respiration, interfering with the respiratory chain • Tetronic and tetramic acid derivatives deregulate development by interfering with nematode moulting	• Products based on microorganisms and/or metabolites. Bacteria: • *Bacillus subtilis* • *Bacillus licheniformis* • *Bacillus firmus* • *Bacillus velezensis* • *Bacillus amyloliquefaciens* • *Pasteuria nishizawae* • *Pseudomonas oryzihabitans* • *Priestia megaterium* Fungi: • *Paecilomyces lilacinus* • *Trichoderma harzianum* • *Trichoderma asperellum* • *Trichoderma koningiopsis* • *Pochonia chlamydosporia*	• Bionematicides have three main functions that prevent nematode attacks: • Biofilm, which protects the plant root • Chemotaxis, which limits the nematode's ability to locate the host plant • Chitinase degrades the eggs, reducing their number in the soil, and the nematode cuticle, reducing the juvenile population • Bacteria have direct and indirect effects with biofilm production. Fungi are parasites of eggs and juvenile nematodes	• Bionematicides must be applied preventively or at the beginning of the infestation, preferably in the sowing furrow, seed treatment, or via soil/boom spray, ensuring direct contact of the microorganism with the rhizosphere	• For nematode management, a set of methods must be adopted. Thus, chemical control can be combined with biological control, taking into account the infestation, soil and climate conditions, nematode species and succession crops

3.1.1. Inoculants

Inoculants function as nitrogen fixers, growth promoters, and nutrient solubilizers. Species of the genus *Bradyrhizobium* are examples of bacteria that promote biological nitrogen fixation in soybeans. The bacterium *Azospirillum brasilense* promotes root growth through the production of phytohormones (e.g., auxins), increasing soil exploration by plants, and is used as a growth promoter for grasses and in soybean co-inoculation.

Products based on microorganisms such as *Bacillus megaterium*, *B. subtilis* and *Pseudomonas fluorescens* help in the solubilization of nutrients. Some strains of these microorganisms produce organic acids capable of forming stable complexes with Fe^{3+}, Al^{3+}, and Ca^{2+}, promoting the release of phosphorus previously associated with these elements. In addition, they secrete enzymes, such as phosphatases, that mineralize organic phosphorus present in the soil, among other mechanisms that increase the availability of this nutrient to plants.

In 2023, a foreign multinational registered in Brazil a product based on the *Methylobacterium symbioticum*, whose label indicates a high capacity for biological fixation of atmospheric nitrogen in corn. However, research has revealed that the commercially used strain, although it offers benefits such as plant growth promotion, does not possess the complete genetic apparatus of nitrogenase and, therefore, does not perform biological nitrogen fixation (Table 1).

3.1.2. Fungicides

Fungal diseases affecting the aerial parts and root system of plants can be controlled through the application of biological products. Bio-inputs used to control foliar diseases are mainly formulated with bacteria of the genus *Bacillus* with biofilm-forming, resistance-inducing, and antibiosis-inducing effects. Biological agents used to control soilborne diseases are mainly formulated based on fungi of the genus *Trichoderma* with effects of parasitism, competition, and antibiosis. For soil diseases, there are commercial products for furrow or boom application, and also for seed treatment.

3.1.2.1. Fungicides for Foliar Diseases

The biofungicides currently available for foliar disease management in the Brazilian market differ substantially in their technological characteristics, reflecting the rapid evolution of biological crop protection. Most products are based on *Bacillus* spp., although formulations range from single-strain inoculants to microbial consortia designed to enhance efficacy through complementary modes of action. Several manufacturers have developed products with proprietary strains, either independently or in collaboration with public research institutions, to target specific agronomic functions. In addition to the living microorganisms, many formulations contain bioactive metabolites such as surfactin, iturin, and fengycin, which disrupt the cell membranes of phytopathogenic fungi. Some manufacturers also disclose the concentration of these metabolites (mg L^{-1}), highlighting their role in product performance. Beyond direct pathogen suppression, *Bacillus*-based biofungicides provide complementary benefits, including antibiosis, biofilm inhibition, induction of plant defense mechanisms, and plant growth promotion.

Considerable variation also exists in the spectrum of registered targets, with some products approved for the control of up to 31 diseases. Collectively, these products are registered against the major soybean foliar diseases, including brown spot, Cercospora leaf spot, anthracnose, and Asian soybean rust. Additional technological innovations include formulations with enhanced residual activity and improved tolerance to high temperatures, which can increase field persistence under tropical conditions. According to manufacturers, most biofungicides are positioned as replacements for multi-site protectant fungicides, whereas a Brazilian company and a Dutch company position their new products as an alternative to site-specific fungicides.

3.1.2.2. Fungicides for Soil-Borne Diseases

The biofungicides available for the management of soil-borne diseases in the Brazilian market exhibit considerable technological diversity in terms of microbial composition, mechanisms of action, and formulation technologies. While most products are based on fungi of the genus *Trichoderma*, formulations containing *Bacillus* spp., either as single strains or as part of microbial consortia, are also commercially available. Many manufacturers have developed products with proprietary microbial strains through in-house research or collaborations with public research institutions to enhance specific agronomic functions. These products employ distinct biological mechanisms, with *Trichoderma* acting primarily through mycoparasitism and degradation of pathogen survival structures, whereas *Bacillus* spp. control diseases through mechanisms such as root biofilm formation, antibiosis, and induction of plant defenses. The range of registered targets varies substantially among products, with some currently approved for the control of up to 11 pathogens, including both fungi and nematodes, although registrations continue to expand over time.

The principal target diseases include white mold and root rot, while several formulations incorporate additional technological innovations such as phytohormone induction, encapsulation technologies that protect the active ingredient, and ultraviolet (UV) protection to improve field persistence. Most products are recommended for integrated use with chemical fungicides, providing complementary benefits through root growth promotion and the reduction of soil pathogen inoculum. Shelf life also varies considerably among commercial formulations, reflecting differences in formulation technologies. Supporting the commercial claims, an independent evaluation conducted by Embrapa in 2025 reported that some commercial biofungicides achieved up to 80% efficacy in controlling white mold, with *Trichoderma* species acting primarily by parasitizing and destroying fungal sclerotia, thereby reducing pathogen survival in the soil.

Biological products developed for seed treatment (ST) and industrial seed treatment (IST) are expanding the range of biological solutions available to soybean growers and, in specific applications, have the potential to replace conventional chemical seed treatments. These products are formulated with both fungal and bacterial microorganisms, including proprietary strains to optimize seed protection and early plant establishment. Their spectrum of activity varies among products, with some demonstrating efficacy against up to nine registered targets, including fungal pathogens and nematodes. The principal target diseases include damping-off and *Fusarium* wilt, although the range of controlled pathogens differs according to the microbial strain and formulation.

Technological innovations extend beyond microbial selection to include specialized formulations incorporating graphite to improve seed coating, protective oils that enhance conidial survival, and secondary metabolites with antifungal activity, all of which contribute to product stability and biological performance. Some products are explicitly positioned as alternatives to chemical seed treatments for the management of *Fusarium* wilt, illustrating the increasing capacity of biological products to replace synthetic inputs in specific applications. Shelf life also varies considerably among commercial formulations, reflecting differences in formulation technologies and storage stability.

3.1.3. Insecticides

Biological insect control is based on four main groups of agents: viruses, bacteria, entomopathogenic fungi, and macroorganisms. For caterpillar control, there are products based on viruses and bacteria (mainly *Bacillus)* and also fungi. In the management of sucking insects, such as whiteflies and other non-lepidopteran insects, fungi, bacteria, and macro-organisms are used.

There are viruses for the main caterpillars that cause commercial damage to crops. The most commonly used bacterium in insect control is *Bacillus thuringiensis* (Bt). The main fungi used for insect control are *Beauveria bassiana*, *Metarhizium anisopliae*, *Metarhizium rileyi*, *Isaria fumosorosea*, and *Isaria javanica*. The main macro-organisms used to control insect pests in soybean crops are the predators *Chrysoperla externa* and *Amblyseius tamatavensis* and the parasitoids *Telenomus podisi* and *Trichogramma pretiosum*.

Unlike disease control, which is usually carried out preventively and according to a schedule, insect control begins with the initial detection of the insect's presence through crop monitoring.

3.1.3.1. Viruses for Caterpillar Control

Baculovirus is a highly specific biological control agent that infects and kills caterpillars (insect larvae) of the target species, without potentially affecting other caterpillar species or other insects. Its action involves the caterpillar ingesting the virus while feeding on leaves treated with the product. With virus replication, the caterpillar's death generally occurs between 3 and 7 days after infection. After death, the caterpillar's body ruptures and new viruses are released onto the leaves, potentially infecting other caterpillars.

The commercial baculovirus products available in the Brazilian market are characterized by a relatively concentrated production landscape and important technological differences in target spectrum and formulation. Five companies are responsible for the production of most commercial virus-based bioinsecticides, with some manufacturers also supplying viral active ingredients to other companies to complement their product portfolios, resulting in products marketed under different brands but sharing the same registration number. Most commercial formulations are designed to control the fall armyworm (*Spodoptera frugiperda*), reflecting the economic importance of this pest in Brazilian agriculture, although products targeting other lepidopteran caterpillars are also available.

Formulation technology represents another important differentiating factor. Solid formulations can be stored without refrigeration, facilitating logistics and field distribution, although they generally have a shorter shelf life. In contrast, liquid formulations typically provide greater storage stability but require refrigerated conditions, with the commercially available products differing in their recommended storage temperatures. Brazilian manufacturers also emphasize partnerships with Embrapa in the development and validation of virus-based products, underscoring the role of public–private collaboration in advancing biological crop protection technologies.

3.1.3.2. Bt for Caterpillar Control

Bacillus thuringiensis- based bioinsecticides are widely used in caterpillar management, standing out as an efficient and sustainable tool within integrated pest management (IPM) programs. The Bt product is applied to the crop and ingested by caterpillars when they feed on the leaves. After ingestion, the protein crystals (Cry toxins) are activated in the insect's gut, promoting the rupture of epithelial cells and leading to feeding cessation and death. Bt does not have a contact action; its effectiveness depends on ingestion, which reinforces the need for good foliar coverage and applications in the early stages of infestation.

The Brazilian market for *Bacillus thuringiensis*-based bioinsecticides is characterized by substantial diversity in microbial strains, target spectrum, and formulation technologies, providing growers with products tailored to different pest management strategies. Most commercial products are based on *B. thuringiensis* var. *kurstaki* (HD-1 strain), which is widely recognized for its high efficacy against lepidopteran pests. However, the market also includes products formulated with proprietary *B. thuringiensis* isolates and combinations with other beneficial microorganisms, such as *Brevibacillus laterosporus*, to broaden biological activity or enhance product performance. Considerable variation is also observed in the number of registered target pests, with some products approved for the control of up to 23 species, reflecting differences in biological spectrum and commercial positioning.

Formulation technology further differentiates the available products. Suspension Concentrate (SC) is the predominant formulation, although Wettable Powder (WP) and Emulsifiable Concentrate (EC) formulations are also commercially available. These formulation technologies influence product stability, ease of application, compatibility with other crop protection products, and operational performance under field conditions, representing an important source of technological differentiation among commercial bioinsecticides.

The strategic use of virus-based and Bt bioinsecticides helps reduce selection pressure and delay the development of resistance in pest insect populations. Brazilian farmers commonly prefer to use Bt in initial applications and viruses in subsequent applications, when there is already a larger population of caterpillars that can be contaminated with the virus.

3.1.3.3. Fungi and Bacteria for the Control of Sucking Insects

Beauveria bassiana is the predominant entomopathogenic fungus used for biological insect control in Brazil, reflecting its broad efficacy and widespread commercial adoption. At the same time, the availability of bacterial bioinsecticides expands the diversity of biological control mechanisms, enabling more robust and complementary integrated pest management (IPM) strategies. A key technological advantage of these products is the diversity of their modes of action: entomopathogenic fungi infect insects directly through contact with the cuticle, whereas bacterial products act through ingestion, targeting the digestive tract of insects feeding on treated plants.

The use of proprietary microbial strains developed by different companies further highlights the technological differentiation within the sector, with potential benefits for environmental adaptation, persistence, and field performance. Commercial products also differ considerably in the number of registered target pests, reflecting variation in their biological spectrum and market positioning. Formulation technology represents another important source of innovation, with wettable powder (WP), oil-dispersible (OD), and suspension concentrate (SC) formulations influencing microbial adhesion, protection of the active ingredient, application efficiency, and overall field performance. Collectively, these products are primarily intended for the management of economically important sucking pests, including whiteflies, mites, stink bugs, and thrips, demonstrating the increasing sophistication of biological solutions available for insect control in Brazil.

3.1.4. Nematicides

Biological control of plant-parasitic nematodes in Brazil relies primarily on bacterial species from the genera *Bacillus*, *Pseudomonas*, and *Priestia*, as well as on nematophagous fungi of the genera *Paecilomyces*, *Trichoderma*, and *Pochonia*. Bacterial products control nematodes through both direct and indirect mechanisms, including biofilm formation on plant roots, which creates a protective barrier, and chemotaxis-mediated interference that reduces the ability of nematodes to locate host plants. Fungal products, in contrast, primarily act by parasitizing nematode eggs and juvenile stages, thereby reducing population establishment in the soil.

The Brazilian market offers biological products registered for the control of all major nematode species affecting the country's principal crops, providing growers with a wide range of management alternatives. Considerable technological diversity exists among these products, including formulations based exclusively on bacteria, fungi, or combinations of both, each relying on distinct and complementary mechanisms of action. Although no single product is currently registered for the control of all economically important nematode species, some products have broader registration scopes than others. However, the number of registered targets should not be interpreted as an indicator of superior technical performance, but rather as the formal spectrum of control approved on the product label. Well-established products have relatively narrower registrations than some recently introduced products, illustrating how registration scope does not necessarily reflect market maturity or field efficacy. An example of recent technological innovation combines *Bacillus* bacteria with nematophagous fungi in a single formulation. This consortium approach has the potential to broaden mechanisms of action and improve biological control, provided that interactions between the microorganisms remain compatible and function synergistically under field conditions.

3.2. The Agronomics of Bio-Inputs

This section examines the agronomic aspects of bio-inputs, focusing on their mechanisms of action, application across different phenological stages, potential to replace or complement chemical inputs, the efficacy of commercially available biological products, and their compatibility with chemical products in spray mixtures.

3.2.1. Mechanisms of Action

Fungi in agricultural bio-inputs act primarily through parasitism (feeding directly on the pathogen), antibiosis (production of metabolites that control pathogens), and competition for space and nutrients. Mycoparasitism is a biological control mechanism in which a beneficial fungus (biocontrol agent) attacks, parasitizes, and feeds on another pathogenic fungus (one that causes disease in the plant). This is a direct form of "parasite of parasite," very common in the use of fungi of the genus *Trichoderma*, used, for example, to control white mold. *Trichoderma* grows on the sclerotia of white mold, rendering them unviable and preventing plant infection.

Bacteria act primarily through growth promotion (with nitrogen fixation, solubilization of nutrients such as phosphorus, and production of phytohormones) and biocontrol (biofilm formation, induction of resistance and antibiosis). Products based on microorganisms such as *Bacillus megaterium*, *B. subtilis* and *Pseudomonas fluorescens* help in the solubilization of nutrients by secreting organic acids that form stable complexes with Fe3+, Al3+, and Ca2+, releasing the P previously bound to these metals. These organisms also produce enzymes such as phosphatases that mineralize organic phosphorus in the soil.

Biofilm in agricultural bio-inputs is a protective structure formed by microorganisms such as bacteria of the genus *Bacillus* that acts as a shield, enhancing the biocontrol of pests and diseases, promoting root growth and increasing resistance to stress. Biofilm also limits the ability of nematodes to locate the host plant.

Induced resistance occurs when beneficial bacteria activate the plant's defense mechanisms before or during pathogen attack. Antibiosis occurs through the production of secondary metabolites, such as surfactin and other bioactive compounds, which bind to the fungal cell membrane, promoting its destabilization, rupture, and consequently, the death of the fungi.

Baculovirus is a highly specific and effective bioinsecticide for controlling caterpillars. Baculoviruses act by being ingested by the caterpillar, infecting and killing the pest. Caterpillars such as *Spodoptera frugiperda*, *Helicoverpa armigera* and *Chrysodeixis includens* can be effectively controlled with the use of highly specific biological products available on the Brazilian market.

Macroorganisms are beneficial insects, mites, and nematodes used as natural enemies of agricultural pests. For example, *Chrysoperla externa* and *Amblyseius tamatavensis* act as predators whose larvae prey on pests and can consume hundreds of insects during their development. Macro-organisms such as *Telenomus podisi* and *Trichogramma pretiosum* act as parasitoids, whose females parasitize the pest's eggs, rendering them unviable before the caterpillar hatches and drastically reducing the population in the field.

3.2.2. Applications in Soybeans Phenology

Controlling fungal diseases, especially foliar diseases, is usually done through scheduled applications of biological and chemical products. Insect control, on the other hand, is based on crop monitoring, with interventions carried out as needed.

The number of fungicide applications varies according to the region and disease pressure, with common applications being seed treatment, during the vegetative stage (often at V3 and V5) and also during the reproductive stage (often at R1, R1+15 days, and R1+30 days). Based on crop monitoring, farmers tend to plan insecticide applications in conjunction with the fungicide application schedule as a way to optimize logistics. When seeds do not undergo industrial seed treatment (IST), the application of inoculants and nematicides is done during seed treatment (ST) carried out on the farm or in the planting furrow.

3.2.3. Biologicals as Potential Substitutes for Chemicals

The use of inoculants as a substitute for nitrogen fertilization in soybeans is a consensus in the scientific community and among farmers. There is also a growing understanding of the effectiveness of bionematicides when compared to chemical nematicides available on the market. However, for all other agricultural practices, bio-inputs are seen as complementary to chemicals, especially for the control of fungi and insects that can have a significant economic impact on crops.

This scenario began to change in Brazil from 2025 onwards, with foliar fungicides being positioned as potential substitutes for chemicals in applications during the vegetative stages of crop development. Some biological companies are already positioning foliar biofungicides as substitutes for multi-site chemicals in the vegetative stages of soybeans according to the following schedule.

1st. V3 - Biological product only

2nd.V5 - Biological + site-specific chemical

3rd. R1 - Multisite chemical + site-specific chemical

4th. +15 days - Multi-site chemical + site-specific chemical

5th. +30 days - Multi-site chemical + site-specific chemical

For soil fungus control, companies typically place the biological agent in the planting furrow to complement the chemical agent, with the function of accompanying root growth and parasitizing fungi to reduce inoculum.

3.2.4. Technology Combination

In addition to potentially replacing some chemical applications, biological products are used in a complementary way to chemical ones, as a form of technology stacking, with the biological product being applied in addition to the chemical. For example, phosphorus biosolubilizers are used in addition to mineral fertilization to improve nutrient availability for the plant.

For insect control, the bacterium *Bacillus thuringiensis* (Bt) and baculoviruses are used as complements to chemicals in caterpillar control, with Bt being preferentially used in the first applications and viruses in subsequent applications, when there is already a larger population of caterpillars that can be contaminated by the virus. For the control of sucking insects, fungi-based products such as *Beauveria bassiana* and bacterial solutions are used in addition to chemicals.

Biological inputs used in a complementary way to chemical inputs bring the benefits of increased effectiveness in pest and disease control, as well as reduced resistance to chemicals, in addition to the possible reduction in the dose of the chemical product considering the dosage range indicated in the product label. In Brazil, bio-inputs have been used in soybean management based on the following possibilities:

- Conventional – With biologicals prioritized over chemicals in the cases of:
    - Inoculants for biological nitrogen fixation in soybeans.
    - Bionematicides used in seed treatment or in the planting furrow prioritized over chemicals for nematode control.
- Substitutes – With biological products positioned by some companies as replacements for chemical fungicides (primarily protectant/ multi-site fungicides) in initial applications, offering potential cost reduction, notably in:
    - In seed treatment - Biofungicides replacing chemical fungicides in seed treatment or in the planting furrow for the control of Fusarium wilt and white mold (e.g., *Trichoderma* with proven high efficacy of some strains).
    - In the vegetative stages - Biofungicides replacing multi-site chemical fungicides in the initial applications of the vegetative stage (various products) and also as substitutes for site-specific chemical fungicides in the first application of the vegetative stage.
- Stacking – With the use of bioinsecticides in a complementary way to chemical insecticides. Stacking technologies bring the benefit of increased effectiveness and reduced resistance to chemical molecules, with emphasis on:
    - *Beauveria bassiana* (various commercial products) for the control of sucking insects.
    - *Bacillus thuringiensis* (Bt) and viruses for caterpillar control.

- Other examples include macroorganisms for insect control, semiochemicals for moths, and foliar fertilizers.

3.2.5. Efficacy of Biologicals and Chemicals

There is scientific evidence regarding the effectiveness of agricultural bio-inputs in controlling pests and diseases and promoting plant growth. Research results show cases where biologicals are less effective than purely chemical control (in Asian soybean rust and powdery mildew, for example) and cases where biologicals combined with site-specific chemicals showed equivalent effectiveness to multi-site and site-specific chemical control (in downy mildew and apple scab) (Table 2).

Some results reveal that commercial biofungicides controlled up to 80% of white mold (*Sclerotinia sclerotiorum*), while products for foliar diseases such as target spot (*Corynespora cassiicola*) had limited performance, with efficacy up to 40%. It is worth noting that bio-input formulations are being improved each year with the possibility of increased efficacy in the future.

Efficacy results were also found for bioinsecticides and bionematicides by different studies cited in Table 2. Bioinsecticides based on the bacterium *Bacillus thuringiensis* and products containing viruses have shown high efficiency in controlling caterpillars. Products based on the fungi *Metarhizium anisopliae* and *Beauveria bassiana* have been successfully tested for the control of stink bugs and sugarcane borers. Bionematicides have been tested for the nematode species *M. javanica*, *P. zeae*, and *M. exigua*, in some cases with greater efficacy than chemical products.

Inoculants have a proven role in biological nitrogen fixation in legumes such as soybeans. Specifically, regarding biological foliar nitrogen fixation, although a product is registered in Brazil, a scientific article revealed that the *Methylobacterium symbioticum* does not possess the complete genetic apparatus of nitrogenase and therefore does not perform biological nitrogen fixation, although it promotes growth (Table 2).

Table 2. Scientific evidence on the effectiveness of agricultural bio-inputs available on the Brazilian market showing the control rate (in %) for different pests and diseases.

Associated Use - Technology Stacking					
Target	**Chemical SE**	**Bio MS + Chemical SE**		**Chemical SE + Chemical MS**	**Source**
Asian soybean rust	53% Picoxystrobin and Cyproconazole	56% Picoxystrobin and Cyproconazole + *B. subtilis* + *B. velezensis* + *B. pumilus*		66% with Chlorothalonil 73% with Mancozeb	Godoy, et al. [5]
Powdery mildew in soybeans	-	73% Trifloxystrobin and Cyproconazole + *Bacillus amyloliquefaciens*		94% with Chlorothalonil 97% with Mancozeb	Dickel, et al. [6]
Downy mildew in soybeans	-	60% Strobilurin + *B. subtilis*		60% Strobilurin + Carboxamide + Mancozeb	Santos, et al. [7]
Apple scab	-	86% Benzovindiflypur + *B. subtilis*		88% Benzovindiflypur + Mancozeb	Ayer, et al. [8]
Alternative Use of Technologies					
Fungicides					
Target	Micro-organism	Biological Solution	Bio Efficacy	Chemical Efficacy	Source
White mould	*B. subtilis* and *T. asperellum*	Up to 80% control with *B. subtilis* QST 713 and *T. asperellum* URM 5911	80%	Up to 100% with Fluazinam/Boscalid	Godoy, et al. [9]

Late season diseases & Target spot	Various biological agents	Up to 40% control with *B. velezensis*, *B. subtilis* and Cerevisane	40%	Up to 80% with various commercial chemical fungicides	Godoy, et al. [9]
Fusariose - Seed treatment	*B. velezensis* and *P. ottowoii*	Up to 80% control with *B. velezensis* BRM046334 and *P. ottowoii* BRM05345	80%	Up to 86% with Maxim Quattro	Brazilian Agricultural Research Company (Embrapa) [10]
Strawberry grey mould	*B. amyloliquefaciens* and *B. subtilis*	Up to 52% control with No-Nema and up to 50% with Bio-Imune	52%	Up to 75% control with Fluazinam	de Oliveira, et al. [11]
Wheat stripe rust / Yellow rust	*B. subtilis*	Up to 60% control with Serenade (*Bacillus subtilis* strain QST713)	60%	Up to 97% with Proline (Prothioconazole)	Koch and Scherwinski-Pereira [12]
Insecticides					
Target	Micro-organism	Biological Solution	Bio Efficacy	Chemical Efficacy	Source
Caterpillars	*B. thuringiensis* (Bt) or Baculovirus	Up to 100% control with *B. thuringiensis* 1641/1644 and >80% with baculovirus for *S. frugiperda*	100%	Up to 87.5% control with Engeo Pleno	Polanczyk, et al. [13]
Stink bugs	*Beauveria bassiana*	Up to 96% control through Strain CECT 20374; cumulative mortality in 14 days	96%	Above 74% with Acetamiprid + Bifenthrin	Boggione, et al. [14]
Sugarcane borer	*Metarhizium anisopliae*	Up to 78% control of the borer through Isolate IBCB 425; drastic reduction in egg viability	78%	Chemical data vary depending on application	Koch and Scherwinski-Pereira [12]
Wax moth (Honeybee pest)	*Beauveria bassiana*	Genetically modified *B. bassiana* for oosporin overproduction. Blastospores reached 97% mortality	97%	-	Mascarin, et al. [15]
Nematicides					
Target	Micro-organism	Biological Solution	Bio Efficacy	Chemical Efficacy	Source
Pratylenchus zeae	*P. oryzihabitans*	Up to 64% in soil and up to 81% in sugarcane root	81%	Up to 60% control with Fluazaindolizine	Costa, et al. [16]
Meloidogyne javanica	*B. subtilis*	Up to 66% with *Bacillus subtilis*	66%	Up to 90% with chemicals	Bonissoni [17]

		2657 in common beans (Product: Furatrop)			
Meloidogyne exigua	*B. amyloliquefaciens*, *B. thuringiensis*, *B. velezensis*	Up to 65.5% control in coffee at 60 days with Biomagno	65%	Up to 91.2% control in coffee crops at 60 days using Verango® Prime	Tamburi [18]
Inoculants					
Target / Function	Micro-organism	Biological Solution		Bio Efficacy	Source
Phosphorus (P) Solubiliser	*B. megaterium* and *B. subtilis*	Up to 24% increase in maize yield with *B. megaterium* CNPMS B119 and *B. subtilis* CNPMS B2084		24% increase in productivity	de Oliveira-Paiva, et al. [19]
Growth promoter	*Azospirillum brasilense*	Inoculated into maize seeds, acts as a growth promoter and reduces nitrogen fertilisation		25% reduction in N fertilisation	Hungria, et al. [20]
Foliar N fixation	*Methylobacterium symbioticum*	The commercial strain SB0023/3 does not produce nitrogenase and, therefore, does not fix N, though it promotes growth		0% nitrogen fixation	Giller, et al. [21]

Note: MS - multi-site; SE - specific-site.
The percentages represent results reported in specific studies and should not be interpreted as expected performance under all cultivation conditions.
The efficiency of bio-inputs depends on the strain used, formulation, environment, management and target pressure.

3.2.6. Compatibility with Chemicals

Farmers tend to mix biological inputs into chemical spray mixtures as a way to optimize farm logistics and avoid additional inputs into the field. This strategy presupposes evaluating the compatibility of biological products with the chemicals in the spray mixture beforehand. Before applying a biological product, it is recommended to check with the manufacturer to ensure that the product is compatible with other technologies used in the spray mixture, such as adjuvants, nutrients, herbicides, fungicides, and insecticides. Attention should be paid to using the correct and compatible adjuvants so that the product reaches its target.

3.3. Adoption

The survey conducted with commercial representatives operating in different Brazilian agricultural regions revealed substantial regional variation in the adoption of bio-inputs among soybean farmers. The highest levels of adoption were observed in Santa Catarina (SC) and the Federal District (DF), followed by the Matopiba region, particularly the states of Piauí (PI) and Bahia (BA) (Table 3). These differences likely reflect regional variations in production systems, technological intensity, pest and disease pressure, and the availability of technical support for biological products.

Among the biological input categories analyzed, the widespread adoption of biofungicides for soil disease management, bionematicides, and biological insect control strategies was particularly notable. Insect control practices included the use of fungal-based products, mainly targeting sucking insects, as well as *Bacillus thuringiensis* (Bt)-based and viral-based bioinsecticides, which are predominantly used for managing lepidopteran pests. As expected, inoculants showed consistently high adoption rates across all evaluated regions, reflecting their established role in soybean production systems.

The regional adoption patterns indicate that bio-inputs are not limited to a single technological niche but encompass multiple applications within soybean production systems. In regions with more intensive adoption, such as SC and DF, farmers reported broader use across several categories, including microbial insecticides, bionematicides, and nutrient-related biological products. Conversely, regions such as Pará (PA) and Rio Grande do

Sul (RS) showed lower overall adoption levels, although specific categories, such as inoculants and Bt-based insecticides, maintained relevant adoption rates.

Table 3. Estimated adoption of eight categories of agricultural bio-inputs among soybean farmers surveyed in different Brazilian regions (% of farmers adopting each bio-input category).

Regional	NE (BA)	NE (PI)	SE (MG-T)	SE (SP)	S (RS)	S (SC)	N (PA)	CO (DF)
Foliar biofungicide	15	12.5	35	30	40	20	10	45
Soil biofungicide	80	12.5	20	50	35	50	10	60
Bionematicide	70	60	25	60	25	50	0	50
Fungal insecticide	50	40	30	50	0	60	0	80
Viral insecticide	10	50	30	0	0	60	1	12.5
Bt insecticide	5	50	5	5	5	70	50	70
Inoculant	90	99	90	80	60	80	90	90
Solubilizer	20	20	15	25	9	80	10	30
Average adoption	42.5	43.0	31.3	37.5	21.8	58.8	21.4	54.7

4. CONCLUSION

This study provides a state-of-the-art assessment of the agronomics of commercial biological products for soybean production in Brazil, focusing on inoculants, biofungicides, bioinsecticides, and bionematicides. The findings demonstrate that farmers already rely on a wide-ranging portfolio of commercially available biological products based on bacteria, fungi, viruses, and macroorganisms, such as parasitoid wasps, to promote plant growth and manage pests and diseases.

In addition to replacing certain chemical applications, such as synthetic nematicides or fungicides in preventive treatments or under conditions of low disease pressure, biological products are frequently used in combination with chemical inputs as part of a technology-stacking strategy. This integrated approach enhances the effectiveness of pest and disease management while reducing selection pressure for resistance to synthetic pesticides.

Adoption levels vary across product categories and according to the technological intensity of farming systems and regions. Inoculants are the most widely adopted biological products, reflecting their long-established role in soybean production. Bionematicides have also emerged as one of the main biological alternatives to synthetic nematicides for preventive treatments, whereas commercial biological herbicides are not yet available on the Brazilian market.

These findings demonstrate that bio-inputs are no longer an emerging or experimental technology but have become an integral component of the management systems adopted by large-scale commodity farmers in Brazil. The Brazilian experience suggests that innovations in agricultural bio-inputs can simultaneously strengthen agricultural productivity, promote sustainable development in the Global South, and foster domestic industrial capabilities, provided that the sector is supported by robust scientific research, effective regulatory frameworks, and rigorous quality control.

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