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Review Article

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Biological resources driving productivity: bioinputs for sustainable plant agriculture in Brazil

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Abstract

Brazil is a world leader in agriculture, playing an important role in world food security. Agriculture has changed drastically over the years in Brazil. Different kinds of technology are being developed to increase production, reduce costs, and to decrease environmental impacts of agriculture. In 2020, the Brazilian Ministry of Agriculture, Livestock, and Supply (MAPA) launched the National Bioinputs Program to promote the adoption of sustainable technologies derived from biological resources, bioinputs, many of which are microbial-based. Bioinputs aim at enhancing agricultural productivity, improving soil health, and mitigate environmental impacts. Bioinputs can be classified into three main groups according to functionality: those that promote plant growth and development, those that serve as biological pest control agents, and those that contribute to soil conditioning or restoration. Each of these categories is further subdivided according to their mode of action. In this review, we will focus on bioinputs currently commercialized in Brazil. Details about these products, including the microorganisms involved, their mode of action, and target crops will be discussed. The advantages and challenges for widespread adoption of this new technology will be explored.

Sustainability Statement

This review is associated with UN Sustainable Development Goal 12 (Responsible Consumption and Production) as the primary focus, through bioinputs' role in reducing reliance on chemical pesticides and inorganic fertilizers, while promoting sustainable agricultural practices. Bioinputs contribute to responsible production systems by offering biological alternatives that minimize environmental impact in agriculture. By replacing synthetic chemical inputs with environmentally friendly biological solutions, bioinputs support the transition toward more sustainable consumption patterns in agricultural production, reducing farming's environmental footprint. Additionally, this work is relevant to SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 6 (Clean Water and Sanitation).

Keywords: bioinputs; bioinoculants; biofertilizers; microbial-based; biopriming

Introduction

Brazil is internationally recognized as a global powerhouse in agricultural production. Among its impressive achievements are the staggering outputs of soybean and corn. In 2023, Brazil secured its position as the world's leading producer of soybeans, with a harvest of 152 million tons. Additionally, the country produced 131 million tons of corn, ranking third-largest corn producer globally, solidifying its status as the world's largest corn exporter (IBGE 2023). Furthermore, Brazil is recognized as the world's leading producer of sugarcane, having yielded 713.2 million tons during the 2023/2024 harvest, primarily for sugar and ethanol production (CONAB 2024). Brazil also holds a prominent global position in coffee production, with a total output of 54.2 million 60-kg bags in 2024 (CONAB 2025).

This large agricultural production demands essential resources, such as fertilizers, crop protection products, and irrigation equipment. However, a significant portion of these inputs is not produced domestically, making imports necessary to meet the needs of Brazil's agricultural sector. In 2024, Brazil imported 41 348 204 tons of NPK fertilizers, representing a 4.8% increase compared to 2023 (ANDA—Associação Nacional Para Difusão de Adubos 2025).

In addition to chemical fertilizers, pesticide use remains high in Brazil. In 2023, Brazil commercialized a total of 759 320 tons of active pesticide ingredients. Although this volume is substantial, it represents a decrease compared to the 800 249 tons sold in 2022 (BRAZIL. IBAMA—Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis 2025a). Based on the cultivated area of ~96.3 million hectares in 2023, this represents ~7.88 kg of active ingredients per hectare (Siqueira and Britto 2023). However, this figure requires careful interpretation. Brazil's agricultural system is characterized by its intensity and efficiency, often supporting 2–3 harvests per year in the same area through the "safrinha" (second crop) system. The "safrinha" system, particularly common with corn cultivation after soybean harvest, significantly increases the effective treated area (Malins 2022). As a result, pesticide use per hectare per year in Brazil cannot be directly compared to that of countries with single annual harvests, as such comparisons overestimate Brazil's pesticide use.

The increased use of chemical fertilizers and pesticides not only negatively impacts agricultural costs, but also may lead to more severe environmental issues, potentially affecting human health. Chemical fertilizers alter soil physicochemical properties, such as its structure, pH, and moisture, impacting micro-

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bial activity (Savci 2012). Their continuous application may increase soil density, potentially leading to compaction, which impairs aeration and drainage. Nitrogen-based fertilizers are a major driver of soil acidification, principally due to the release of hydrogen ions (H^+) during the nitrification process. Furthermore, the excessive application of these fertilizers enhances the leaching of nitrates, as well as essential cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), into adjacent water bodies. The soil microbiota is negatively affected, with reduced microbial diversity and impaired functions such as nutrient cycling. Additionally, excessive fertilizer use increases salinity, inhibiting processes like nitrification. These impacts compromise soil quality and agricultural productivity (Dar et al. 2021).

While chemical pesticides are indispensable for enhancing agricultural productivity, their widespread use raises significant concerns due to their capacity to contaminate soil, water, and food sources, thereby posing substantial risks to human health (Ahmad et al. 2024). Notably, organophosphate and organochlorine pesticides have been repeatedly linked to the onset of neurodegenerative disorders, including Parkinson's and Alzheimer's diseases (Chen et al. 2024, Samareh et al. 2024). Furthermore, a range of pesticide classes, such as carbamates, pyridazinones, organochlorines, triazoles, and N-nitroso compounds, are well-documented for their carcinogenic and teratogenic properties, contributing to increased incidences of cancer and developmental abnormalities in exposed populations (Louati et al. 2023).

In 2015, the United Nations member states adopted the 2030 Agenda for Sustainable Development, a comprehensive framework aimed at fostering peace, prosperity, and sustainability through 17 Sustainable Development Goals (SDGs) (United Nations 2016). This agenda envisions a world in which consumption and production patterns, as well as the use of natural resources, are environmentally sustainable. Within this context, the use of bioinputs in agriculture contributes directly to the advancement of several key SDGs—particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action) (United Nations 2015).

Bioinputs

The word "bioinput" has been used in different ways in the scientific literature, with no consensus definition. In this review, bioinputs refer to products or technologies derived from biological resources, such as microorganisms, plant extracts, or other natural substances, used to enhance productivity and sustainability in agriculture (Carvalho Vidal and Pereira Dias 2023). Although many bioinputs present environmental advantages over conventional chemical inputs, such as greater biodegradability and lower environmental persistence, their safety and ecological impact must be assessed individually rather than presumed safe solely due to their natural origin. The toxicity and ecological effects of both natural and synthetic substances are determined by their specific chemical characteristics, application rates, and environmental behavior (Smith and Perfetti 2020). When properly evaluated and regulated, bioinputs play a critical role in sustainable agricultural systems, including organic farming and agroecological practices (Carvalho Vidal and Pereira Dias 2023).

To strengthen and expand the use of bioinputs in Brazilian agriculture while reducing reliance on synthetic inputs, the Ministry of Agriculture, Livestock, and Supply (MAPA) launched the National Bioinputs Program in 2020. This initiative aims to promote the adoption of sustainable technologies derived from biological resources, including microorganisms, plant extracts, and other naturally occurring agents, to enhance agricultural productivity, improve soil health, and mitigate environmental impacts. Additionally, the program seeks to stimulate research, foster innovation, and facilitate the dissemination of ecological agricultural practices (Brazil 2020).

For that, MAPA issued Instrução Normativa No. 61/2020, which specifies definitions, technical requirements, guarantees, tolerances, registration procedures, packaging, and labeling standards for organic fertilizers and biofertilizers of biological origin destined for agricultural use. This normative framework ensures that bioinput producers adhere to rigorous quality criteria while facilitating market access for biofertilizer and soil conditioner products (MAPA and SDA 2020).

The Brazilian National Bioinputs Law (Law No. 15.070/2024), issued on December 23, 2024, establishes a comprehensive regulatory framework for biological inputs used in agricultural, livestock, aquaculture, and forestry systems. This law defines bioinputs to include products of plant, animal, or microbial origin, as well as those derived from biotechnological processes, encompassing biofertilizers, soil conditioners, biostimulants, semiochemicals, metabolites, macromolecules, and biological control agents. It introduces a single-registration pathway for multifunctional products, exempts on-farm production for private use from formal registration requirements, and assigns the Ministry of Agriculture, Livestock and Supply (MAPA) the authority for registering establishments and products (Agência Senado 2014, BRAZIL 2024).

The National Association for the Promotion and Innovation of the Biological Industry (ANPII Bio) is the leading representative organization for the biological inputs industry in Brazilian agriculture. Currently, ANPII Bio comprises >50 member companies, including both producers and distributors of biological inputs. While the association represents a significant portion of the Brazilian bioinputs industry, it does not encompass all entities operating within this sector (ANPII BIO 2025a). According to data from ANPII Bio, in 2024, more than 18 million liters or kilograms of inoculants were delivered across Brazil, resulting in approximately R$527 million in sales. The primary inoculant products commercialized were based on the microorganisms *Bradyrhizobium*, *Azospirillum*, and *Pseudomonas*. Market projections indicate an estimated growth rate of 12.4% for 2025. Soybean was the principal crop utilizing these biological inputs, followed by maize. Among Brazilian states, Mato Grosso recorded the highest consumption of these products, reflecting its leading role in national agricultural production (ANPII BIO 2025b).

In the Brazilian market for biological crop protection products (biodefensives), ~11.2 million liters or kilograms were delivered in 2024, generating sales revenue of around R$892 million. Projections for 2025 indicate an anticipated market growth rate of 20.4% for biodefensives. Among the different classes of biodefensives, fungicides accounted for the largest share, representing ~37.9% of total purchased value on these products. Nematicides followed, comprising 25.8% of the market value. Soybean cultivation was identified as the principal agricultural sector utilizing these biological solutions, reflecting the crop's significant role in the adoption of sustainable pest management practices within Brazilian agriculture (ANPII BIO 2025b).

Economic analyses indicate potential savings of up to US $5.1 billion annually by substituting chemical fertilizers with microbial inoculants in graminoid crops such as rice, maize, wheat, and sugarcane, alongside reductions of 18.5 million tons of CO_2 emissions (MAPA).

Brazil's bioinput sector is distinguished by a predominance of microorganism-based products, a strong domestic research pipeline, and regulatory frameworks tailored to its tropical context. Globally, biofertilizers and biostimulants are a growing market, yet their composition and application differ markedly between Brazil and other regions. Brazil is one of the biggest producers of microbial inoculants, with ~97% of its inoculants produced domestically and only 3% imported, mainly from Argentina and Uruguay (Soares et al. 2023). In contrast, the global biofertilizer market, which reached USD 2.31 billion in 2023 (Global Market Insights 2024), is dominated by broader portfolios of nitrogen-fixers, phosphate solubilizers, and potassium-mobilizing microbes with major suppliers based in Europe, North America, and Asia (Soares et al. 2023).

The integration of bioinputs into Brazilian cropping systems has led to measurable declines in both synthetic fertilizer and chemical pesticide use under real-world conditions. In soybean, the nationwide adoption of rhizobial inoculants, applied to nearly 80% of the 36 million tons under cultivation, has virtually replaced the need for synthetic nitrogen fertilizers, saving ~20 million tons of N per year (equivalent to 43 million tons of urea) that would otherwise be applied to the soil (Bryce 2022). In maize systems, field trials of a proprietary microbial fertilizer in collaboration with the University of Londrina demonstrated that bioinputs can maintain agronomic performance while reducing nitrogen application rates by 50% (AgriBusiness Global Staff 2023).

Bioinputs can be classified into three main groups (Fig. 2) based on their functionality: (i) those that promote plant growth and development, (ii) those that serve as biological pest control agents, and (iii) those that contribute to soil conditioning or restoration. Each of these categories is further subdivided into specific subgroups according to their mode of action and biological mechanisms (Bullor et al. 2024). Notably, a single bioinput often performs multiple functions simultaneously for example, promoting plant growth while also protecting against pests and diseases. Additionally, the mechanisms underlying these effects are not always fully understood. The following sections provide an in-depth discussion of each category and its respective subgroups.

Plant growth promotion bioinputs

Plant growth can be enhanced through various types of bioinputs, including biofertilizers, biostimulants, and organic fertilizers. In this review, biofertilizers are defined strictly as preparations of beneficial microorganisms, such as nitrogen-fixing bacteria or phosphate-solubilizing fungi, that colonize the rhizosphere or plant interior to improve nutrient availability and uptake. Unlike biopesticides, biofertilizers do not primarily act by suppressing pests or pathogens but by directly supplying or mobilizing essential nutrients for plant nutrition. By contrast, plant biostimulants comprise substances and/or microorganisms whose primary function, when applied to the plant or its rhizosphere, is to trigger or enhance endogenous physiological processes. These processes include improved nutrient use efficiency, increased tolerance to abiotic stresses, and enhanced crop quality, independently of any direct nutrient provision (Bullor et al. 2024, Santos et al. 2024).

Biostimulant formulations may contain microbial inoculants, algal extracts, humic and fulvic acids, protein hydrolysates, or chitosan, but their mode of action is the stimulation of plant metabolic pathways rather than supply nutrients itself. Organic fertilizers, on the other hand, are plant- or animal-derived materials that enrich soil fertility, support microbial activity, and improve soil structure (e.g. vermicompost). Their gradual decomposition enables sustained nutrient release and enhances organic matter content (Bullor et al. 2024, Santos et al. 2024). In the following sections each of these plant growth-promoting bioinput categories will be discussed in detail.

Biofertilizers

Biofertilizers can be defined as living or dormant microorganisms, including bacteria, fungi, and algae, and play a crucial role in enhancing soil fertility by facilitating key nutrient-related processes. These microorganisms contribute to atmospheric nitrogen fixation, converting inert nitrogen gas into bioavailable forms that plants can assimilate. In addition, some biofertilizers are focused in the solubilization and mobilization of soil nutrients, making essential elements such as phosphorus and potassium bioavailable to plants (Bullor et al. 2024).

Biological nitrogen fixation

Nitrogen is the macronutrient most demanded by plants in terms of quantity, as it plays a critical role in the formation of fundamental molecules such as amino acids, proteins, nucleic acids, and chlorophyll. It is absorbed in the form of nitrate (NO_3^-) and ammonium (NH_4^+). Adequate nitrogen availability is critical for vigorous growth, increased biomass production, and enhanced photosynthetic efficiency (Wang et al. 2024).

Nitrogen-based fertilizers have greatly increased agricultural productivity, but plants absorb only about 50% of the applied nitrogen. The rest is lost through leaching, volatilization, and runoff, leading to economic losses and environmental harm (Govindasamy et al. 2023).

The excessive use of nitrogen-based chemical fertilizers can lead to soil acidification that reduces fertility by decreasing the bioavailability of essential nutrients such as calcium, magnesium, and phosphorus through leaching. Acidic conditions also suppress beneficial soil microorganisms, reducing microbial diversity and disrupting key processes such as nutrient cycling. As a result, both soil health and crop productivity are adversely affected. Furthermore, prolonged application of nitrogen fertilizers diminishes the activity of critical soil enzymes, such as ureases, nitrate reductases, nitrite reductases, and catalases (Zhang et al. 2024).

Eutrophication is another significant environmental issue associated with the excessive use of nitrogen- and phosphorus-based chemical fertilizers. These nutrients can accumulate in aquatic ecosystems, promoting excessive algal growth, disrupting the balance of native organism populations (Madjar et al. 2024). Denitrification is also an environmental issue linked to nitrogen-based fertilizer use. As noted earlier, not all applied nitrogen is absorbed by plants; the excess can be

Figure 1. Impacts of biological nitrogen fixation in tropical agroecosystems. The high productivity of Brazilian sugarcane at low cost is largely due to N_2 fixation by diazotrophic bacteria, a process extensively investigated by Johanna Döbereiner (center photo). This natural process, a cornerstone of sustainable agriculture in tropical regions, reduces reliance on synthetic nitrogen fertilizers, bringing economic, environmental, and social benefits. An important indirect environmental benefit is the reduction of GHG emissions, as biological fixation decreases CO_2 from energy-intensive synthetic fertilizer production and limits microbial denitrification, which liberates the GHG N_2O, and occurs when excessive amounts of synthetic nitrogen fertilizers are present in soil.

used by soil microorganisms in the denitrification process. Under anaerobic conditions, these microbes convert nitrate into gaseous nitrogen (N_2) and nitrous oxide (N_2O) by using oxygen from nitrate molecules. Importantly, N_2O is a powerful greenhouse gas that significantly contributes to global warming. Both gases are ultimately released into the atmosphere (LR et al. 2020).

Biological nitrification inhibition (BNI) represents a natural plant-mediated mechanism where certain species release bioactive compounds from their root systems to suppress soil nitrification processes, thereby retaining nitrogen in the more stable ammonium form and reducing nitrous oxide emissions, a large contributor to global warming (Subbarao et al. 2009a, Byrnes et al. 2017).

Among tropical forage species widely cultivated in Brazil, *Brachiaria humidicola* exhibits a high BNI capacity, attributed primarily to the root exudation, this inhibitor is called brachialactone, a unique cyclic diterpene that accounts for 60%–90% of the total nitrification inhibitory activity released from the roots (Subbarao et al. 2009a). *Megathyrsus maximus* (Guineagrass) also demonstrates notable BNI capacity, with phenotypic screening of 119 germplasm accessions of Guineagrass revealing nitrification inhibition ranging from 30% to 70% (Villegas et al. 2020).

Additionally, cereal crops like sorghum exhibit significant BNI activity through the production of sakuranetin and sorgoleone compounds (Subbarao et al. 2009b). Crop rotation between soybean and sorghum represents a practical strategy for incorporating biological nitrification inhibition (BNI) compounds into agricultural systems. *Sorghum bicolor* naturally synthesizes secondary metabolites such as sakuranetin, sorgoleone, and methyl 3-(4-hydroxyphenyl)propionate (MHPP), all of which have demonstrated BNI activity (Qin et al. 2024). Studies have shown that high-BNI sorghum cultivars, when used in rotation, can enhance soil ammonium retention and increase nitrogen availability for subsequent crops, such as wheat (Vega-Mas et al. 2024).

The integration of BNI-enabled plants into Brazilian agricultural systems aligns with the country's National Program for Biobased Agricultural Inputs, which emphasizes sustainable intensification and reduced environmental impact. The economic implications are substantial, as enhanced nitrogen retention through BNI could reduce fertilizer requirements and associated costs while contributing to greenhouse gas mitigation targets. The scientific evidence supports biological nitrification inhibition as a viable and environmentally beneficial technology for Brazilian agriculture, with documented effectiveness in tropical forage systems and promising potential for cereal crop integration, positioning Brazil to leverage this natural phenomenon for sustainable agricultural intensification.

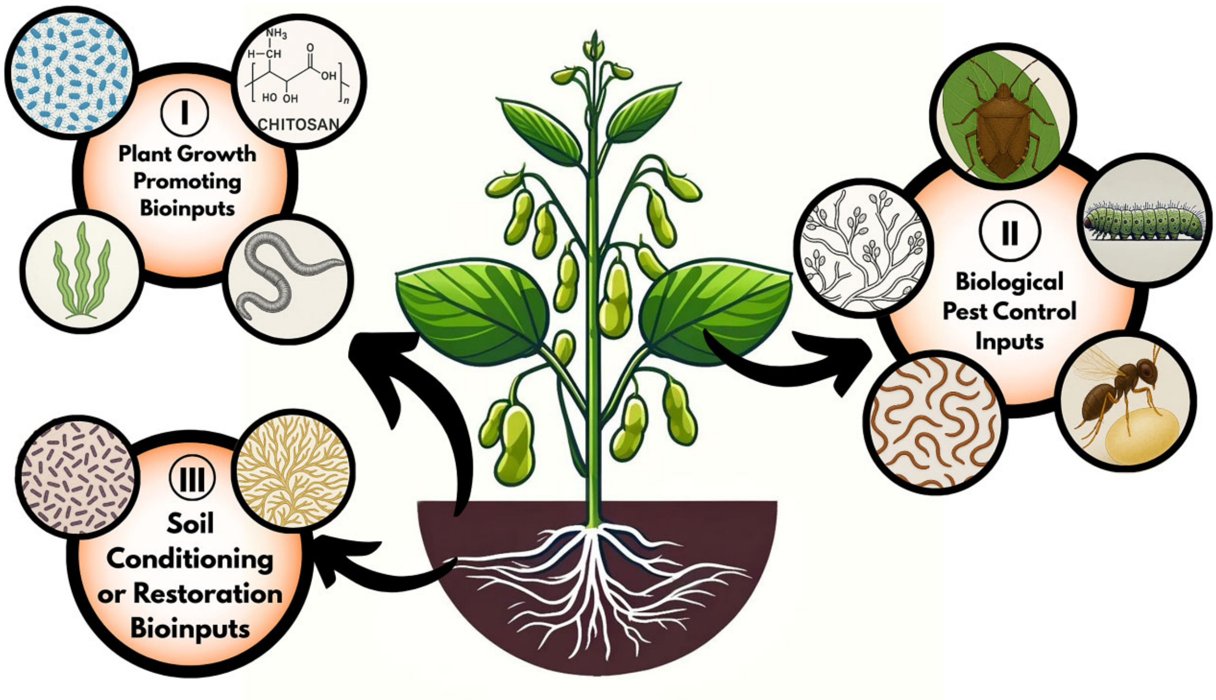

Figure 2. Bioinput categories. Bioinputs can be classified as (I) plant growth promoting bioinputs, (II) biological pest control inputs, and (III) soil conditioning or restoration bioinputs. I: Plant growth promoting bioinputs, represented clockwise, are phosphate solubilizing bacteria (biofertilizer), chitosan (biostimulant), vermicompost produced by earthworms (organic fertilizers), and algae extracts (biostimulants); II: Biological pest control inputs, represented clockwise, are semiochemicals (stink bug), bioinsecticides (caterpillar), biological control of invertebrates (parasitoid wasp), bionematicides (nematodes), and biofungicides (fungi); III: Soil conditioning or restoration bioinputs, represented clockwise, by fungi and bacteria that act as bioremediators, biorestorers, and biotransformers.

Among the microorganisms capable of performing biological nitrogen fixation are two main groups: free-living and symbiotic microorganisms. Free-living biological nitrogen fixation is carried out by different microorganisms, including heterotrophic bacteria (e.g. *Azotobacter*, *Beijerinckia*, and *Clostridium*), autotrophic bacteria (e.g. *Cyanobacteria* like *Anabaena* and *Nostoc*), and archaea. This nitrogen fixation is a key step for nitrogen cycling within ecosystems (Ladha et al. 2022).

Microbial bioinputs that perform biological nitrogen fixation are essential for sustainable, efficient agriculture. These microorganisms convert atmospheric nitrogen into plant-assimilable forms, such as ammonia, thereby reducing the dependence on synthetic nitrogen fertilizers. The microorganisms responsible for this conversion are known as diazotrophs. Within this group are symbiotic bacteria capable of establishing mutualistic associations with specific host plants, most notably those in the legume family Fabaceae, as well as plants of the genus *Parasponia* and actinorhizal species (Bruijn 2015).

The history of biofertilizers is deeply intertwined with the history of Brazil, largely due to the pioneering work of Johanna Döbereiner (Fig. 1), a Brazilian scientist born in Czechoslovakia, who revolutionized agriculture through her research on tropical biological nitrogen fixation (Embrapa 2016). Johanna Döbereiner made pioneering contributions to the understanding of biological nitrogen fixation in non-leguminous crops, particularly sugarcane and maize. Her leadership in research led to the identification of key diazotrophic bacteria, such as *Azospirillum brasilense* and *Herbaspirillum seropedicae*, which colonize the rhizosphere and roots of grasses. Döbereiner demonstrated that, under Brazilian conditions, sugarcane can fix substantial amounts of nitrogen biologically, supporting its high productivity with minimal nitrogen fertilizer input. Her work established the ecological and physiological foundations for exploiting plant–microbe interactions in sustainable agriculture (Baldani and Baldani 2005).

Her groundbreaking discoveries significantly reduced the reliance on chemical nitrogen-based fertilizers in Brazil by promoting the use of bioinputs based on microorganisms capable of biological nitrogen fixation (Dobereiner 1997). As a result of her research, Brazil saves over USD 2 billion annually on nitrogen fertilizers in soybean cultivation alone, due to the effective application of nitrogen-fixing microorganisms. Her work's profound impact led to a Nobel Prize nomination in Chemistry in 1997, distinguishing her as one of the few Brazilians to receive such a prestigious recognition (Embrapa 2016).

Table 1 presents an overview of biofertilizers commercially available in Brazil, their microbial composition, and their main modes of action. The widespread use of nitrogen-fixing bacteria such as *Azospirillum brasilense*, *Bradyrhizobium japonicum*, and *Bradyrhizobium elkanii* is suggestive of a strong emphasis on biological nitrogen fixation to increase crop yields. Products like Azoscoop, Azototal, and AZOTROP also entail the production of phytohormones in the form of indoleacetic acid synthesis for promoting plant growth as well as nutrient acquisition. Some products, such as BIOPASTO, are multi-tasking, acting on nitrogen fixation, abiotic stress tolerance induction, and phosphate solubilization with the aim of optimizing plant resistance and cycling of nutrients in the soil. The occurrence of plant growth-promoting bacteria such as

Table 1. Examples of biofertilizers commercially available in Brazil.

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
Azoscoop	Coopavel	Embrapa soybean and coopavel	*Azospirillum brasilense* Ab-V5 and Ab-V6	Biofertilizer; biostimulant	2025	Brazil	Synthesis of phytohormones (indoleacetic acid) and nitrogen fixation	Inoculation in corn crops	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/12818/azoscoop---inoculante-para-a-cultura-do-milho
Azototal	TOTAL BIOTECNOLOGIA	Embrapa soybean (in partnership with other companies)	*Azospirillum brasilense*	Biofertilizer; biostimulant	2011	Brazil	Phytohormone production; Atmospheric nitrogen fixation	Seed inoculation in grains, cereals, and pastures	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/5459/inoculant-for-brachiaria-grasses https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/11443/inoculante-para-graos-cereais-e-pastagens
AZOTROP	Biotrop	Biotrop	*Azospirillum brasilense* Ab-V5 and Ab-V6	Biofertilizer; biostimulant	—	Brazil	Biological nitrogen fixation; Phytohormone production	Seed treatment in corn, wheat, pastures, soybeans, beans, and rice	https://biotrop.com.br/produto/azotrop/
Biomax Premium Soja	Vittia	Vittia	*Bradyrhizobium japonicum* (SEMIA 5079 + SEMIA 5080)	Biofertilizer	—	Brazil	Nitrogen fixation	Seed or foliar application	https://vittia.com.br/produto/biomax-premium-liquido-soja/

Table 1. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
BIOPASTO (3 products)	Biotrop	Embrapa soybean (in partnership with other companies)	*Azospirillum brasilense* and *Pseudomonas fluorescens*	Biofertilizer; biostimulant; biosolubilizer	2021	Brazil	Phytohormone production (indoleacetic acid); Biological nitrogen fixation; Induction of abiotic stress tolerance; Phosphate solubilization; ACC deaminase production; Siderophore synthesis	Seed or foliar inoculation in Brachiaria grasses	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/8612/multifunctional-inoculant-for-pastures-with-brachiaria-grasses https://biotrop.com.br/produto/biopasto/
Combio	Innova agrotecnologia	Embrapa agrobiologia (in partnership with other companies)	BR 29 *Bradyrhizobium elkanii*, BR 10788 *Bacillus subtilis*, BR 10141 *Paraburkholderia nodosa*	Biofertilizer	2024	Brazil	Biological nitrogen fixation; Growth promotion; Prevention against seed-borne pathogenic fungi	Seed inoculation in soybeans	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/11287/bioproduto-com-acao-na-fixacao-de-nitrogenio-e-na-promocao-de-crescimento-de-plantas https://www.innovaagro.com.br/produto/combio
CRONOS TSI	Biotrop	Biotrop	*Bradyrhizobium japonicum* SEMIA 5079 and SEMIA 5080	Biofertilizer	—	Brazil	High-efficiency biological nitrogen fixation	Pre-planting seed treatment in soybeans	https://biotrop.com.br/produto/cronos-tsi/
NITROSPHERA ELKANII TURFA	Biosphera agro solutions	Biosphera agro solutions	*Bradyrhizobium elkanii* (SEMIA 5019/587)	Biofertilizer	—	Brazil	Nitrogen fixation	Seed application in soybeans	https://biosphera.agr.br/package/nitrosphera-elkanii-turfa/

Table 1. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
NITROSPHERA FUSION	Biosphera agro solutions	Biosphera agro solutions	*Bradyrhizobium elkanii* SEMIA 5019 and *Bradyrhizobium japonicum* SEMIA 5079	Biofertilizer	—	Brazil	Nitrogen fixation	Furrow application during sowing	https://biosphera.agr.br/package/nitrosphera-fusion/
Utrisha N	Corteva agriscience	Symborg business development	*Methylobacterium symbioticum* SB23	Biofertilizer	2021	Brazil	Foliar nitrogen fixation	Foliar application	https://www.corteva.com.br/produtos-e-servicos/biologicos/utrisha-n.html

Bacillus subtilis and *Paraburkholderia nodosa* in Combio also combine plant growth promotion and disease suppression.

The contribution of bioinputs to sustainable yield enhancement has been quantified in maize; seed inoculation with *Azospirillum brasilense* consistently increases grain yield by a mean of 5.4% under Brazilian field conditions, alongside a 12.1% increase in root mass and a 4.3% rise in leaf nitrogen concentration, as demonstrated in a meta-analysis of 103 trials conducted between 2010 and 2021 (Barbosa et al. 2022).

In a field trial involving co-inoculations with three bacterial strains, *P. fluorescens*, *B. subtilis*, and *A. brasilense*, all inoculated treatments resulted in enhanced crop yields. The experiment was conducted with maize, and yield data were compared to a non-inoculated control group. The control plots produced an average yield of 1486.67 kg/ha, whereas the plots inoculated with *Pseudomonas fluorescens* and *Bacillus subtilis* yielded 1699.33 kg/ha, representing an approximate increase of 14% (Barros et al. 2023).

Despite the growing diversity of available biofertilizers, a significant gap remains concerning their long-term performance across multiple cropping systems and under diverse edaphoclimatic conditions.

Bio-solubilizing microorganisms

Plant growth-promoting microorganisms (PGPM), mostly found in the rhizosphere, enhance nutrient availability in the soil and support plant development, making them valuable for agriculture. Phosphorus (P) plays a crucial role in root development and cellular energy transfer, making it one of the key mineral macronutrients required for optimal plant development. It accounts for ∼0.2% of plant dry matter, while it is estimated that 30%–50% of the total P in soil originates from organic sources (Rodríguez and Fraga 1999). However, despite the occurrence of P in soils and applications via fertilizers, a large amount of this nutrient is adsorbed and becomes unavailable to plants (Pavinato et al. 2020). Therefore, only a small fraction is readily available for plant uptake, as P is predominantly present in insoluble forms of calcium (Ca), iron (Fe), and aluminum (Al) phosphates (PANG et al. 2024). Phosphorus deficiency can hinder growth and disrupt essential physiological processes, including photosynthesis, respiration, energy management, cell division, and cell expansion (OLIVEIRA-PAIVA et al. 2022).

Given the critical importance of phosphate and the fact that a significant portion of applied P fertilizers becomes immobilized in the soil, there is an increasing demand for more sustainable, efficient, and economically viable strategies to improve its availability to plants. Microorganisms such as bacteria, fungi, actinomycetes, and cyanobacteria can be used as inoculants to improve P bioavailability in soils, as well as its uptake by plants. Among phosphorus-solubilizing bacteria, genera such as *Bacillus*, *Pseudomonas*, *Actinobacteria*, and *Burkholderia* have been extensively studied and are distinguished for their roles in biofertilization and plant biostimulation (Kour et al. 2021). Among the mycorrhizal fungi, several genera—including *Penicillium*, *Fusarium*, *Aspergillus*, and *Trichoderma*—have been reported to possess phosphorus-solubilizing capabilities (Silva et al. 2023). Also, phosphate-solubilizing cyanobacteria were documented in the literature, including notable genera such as *Anabaena*, *Westiellopsis*, *Calothrix*, and *Scytonema* (Yandigeri et al. 2010, Sharma et al. 2013).

Numerous mechanisms of phosphate dissolution by microorganisms have been reported, and these can vary depending on the form of phosphate present on the soil. For inorganic P sources (Fe–P, Al–P, and Ca–P), phosphate-solubilizing microorganisms (PSMs) secretion of organic and inorganic acids decrease the pH of the surrounding environment, thereby facilitating the solubilization of phosphate complexes into ortho-phosphate. Solubilization of complexes enhances phosphate availability for plant uptake and utilization (Oteino et al. 2015). In the case of organic P sources, which are estimated to comprise 30%–50% of the total soil P, phosphate release by phosphate-solubilizing microorganisms generally occurs through mineralization mediated by extracellular enzymatic activity, involving enzymes such as phytases, phosphatases, and phosphonatases (Sharma et al. 2013). Additionally, siderophore production and exopolysaccharide secretion by phosphate-solubilizing microorganisms can directly influence phosphorus assimilation by plants (Rawat et al. 2021, Pang et al. 2024). BiomaPhos, introduced in 2019, represents the first commercially available Brazilian inoculant developed with a focus on phosphate solubilization. Its development was supported by extensive *in vitro* assays and controlled greenhouse studies, wherein native strains of *Bacillus megaterium* CNPMS B119 and *B. subtilis* CNPMS B2084 demonstrated a pronounced ability to enhance phosphate assimilation by plant root systems (Velloso et al. 2020). A study conducted in 2020 evaluated crop productivity during the 2018/2019 and 2019/2020 growing seasons in fields where BiomaPhos was applied. In inoculated areas, maize crops exhibited an average yield increase of 8.6%, while soybean crops showed an average yield increase of 6.3%. In both maize and soybean production systems, the yield gains resulting from BiomaPhos inoculation exceeded the cost of application. In 2019 alone, ~350 000 hectares of maize and soybean crops were treated with BiomaPhos (Oliveira et al. 2020).

Potassium (K) is another extremely important macronutrient for plant development, being extensively applied as a fertilizer in agriculture. Although it does not contribute structurally, potassium plays a critical role in numerous physiological and metabolic processes in plants (Wang et al. 2012). Despite being one of the most abundant elements on Earth, only a small fraction of soil potassium is readily available to plants, as most of it remains locked in insoluble mineral forms.

Biosolubilization of silicate rocks using potassium-solubilizing Microorganisms (KSM) is a promising strategy to enhance K availability. Various bacteria and fungi have been shown to solubilize potassium from silicate minerals through biochemical decomposition processes (Sattar et al. 2019). The primary mechanisms by which KSM facilitate the solubilization of potassium-bearing minerals include the production of organic and inorganic acids, as well as acidolysis through proton release. Additional mechanisms involve chelation, exchange reactions, and the secretion of polysaccharides (Etesami et al. 2017).

In Brazil, there is a significant demand for the prospecting and development of KSM, as the main challenge related to potassium in Brazil lies in the limited availability of highly soluble national potassic rock sources. The main sources used worldwide for fertilizer production, water-soluble potassium salts derived from evaporite deposits, are scarce in Brazil, and domestic production remains insufficient to meet the country's internal demand for potassium-based fertilizers, positioning Brazil as the world's largest importer of K. Although primary minerals with relatively high potassium content, such as biotite, mica schist, potassium feldspar, and verdete, are present in various regions of Brazil, these rocks exhibit slow dissolution rates and require specific soil and mineral conditions to effectively release the nutrient, often resulting in potassium availability that is insufficient to meet the nutritional demands of agricultural crops (Alves et al. 2021). KSM can play a role in solubilizing these forms such that plants can absorb it.

Although no commercial KSM-based products have yet been formulated domestically, numerous species of KSM have been described in the scientific literature. Among the identified potassium-solubilizing bacteria (KSB) are *Acidothiobacillus ferrooxidans*, *Paenibacillus* spp., *P. mucilaginosus*, *P. frequentans*, *P. glucanolyticus*, *Bacillus mucilaginosus*, *B. edaphicus, B. circulans, Arthrobacter* sp., *Enterobacter hormaechei, Cladosporium* sp., *Aminobacter* sp., *Sphingomonas* sp., and *Burkholderia* sp. Among fungi, the genera *Penicillium, Cladosporium, Aspergillus*, and mycorrhizal fungi, such as *Glomus*, are particularly notable (Meena et al. 2016).

Biostimulants

Biostimulants are formulations of substances and/or microorganisms, such as algal extracts, humic and fulvic acids, protein hydrolysates, chitosan, or microbial inoculants, whose primary function, when applied to plants or the rhizosphere, is to activate endogenous physiological and biochemical pathways rather than to supply nutrients directly. By modulating plant metabolism, biostimulants enhance nutrient use efficiency, optimizing root uptake and assimilation of available elements. They also bolster plant resilience by inducing stress-response mechanisms, improving tolerance to abiotic challenges like drought, salinity, and temperature extremes (Bullor et al. 2024).

These substances can be applied directly to plants, seeds, or soil, aiming at the increase of crop productivity, improving seed and crop quality, and even stimulating root development. Furthermore, biostimulants can play a key role in achieving more sustainable agricultural production, while simultaneously stimulating other biological processes, and potentially enhance crop quality characteristics, including yield, nutritional content, and post-harvest shelf life (Du Jardin 2015). In 2021, Embrapa, in collaboration with NOOA Agricultural Science and Technology, developed the bioinput Auras, based on the rhizobacterium *Bacillus aryabhattai*, isolated from the rhizosphere of *Cereus jamacaru* (mandacaru), a cactus native to the Caatinga, a semi-arid biome found in the Northeastern region of Brazil. These bacteria enhance plant tolerance to water stress and are the first product officially registered in Brazil with this specific function. Auras is applied directly to seeds at planting, and through its establishment in the plant root system, *B. aryabhattai* produces exopolysaccharides that help retain root hydration. Additionally, it modulates plant physiology, improving responses to water deficit. Under drought conditions, Auras is estimated to prevent yield losses of 6 to 8 bags of maize per hectare, with an application cost equivalent to approximately half a bag of maize per hectare (Kavamura et al. 2013).

Furthermore, to achieve a healthy development of the crops, optimal cultivation conditions are required throughout the entire growth period of the plant, which can be interfered by abiotic and biotic stresses, restricting the crops from reaching their full yield potential (Yakhin et al. 2017). Those stresses can be mitigated by providing macro- and micronutrients, appropriate irrigation management, and plant growth regulators (PGRs), which consists in plant hormones such as auxins, cytokinins, gibberellins, strigolactones, and brassinosteroids (Rademacher 2015). In this context, biostimulants appear to be an efficient alternate/additional way of regulating the plant growth promotion through stimulating physiological processes in plants, increasing yield, preserving soil health, and ensuring a non-toxic and safe product for humans and the environment (Kisvarga et al. 2022, Gupta et al. 2023).

There is some inconsistency in the scientific literature regarding the classification of biostimulants types, this review will adopt five main classes: (i) beneficial microorganisms; (ii) humic and fulvic acids; (iii) protein hydrolysates; (iv) seaweed extracts; and (v) chitosan and other biopolymers.

Beneficial microorganisms

Microorganisms can promote plant biostimulation through several mechanisms, which can be direct (i.e. nutrient acquisition and phytohormone production) or indirect (i.e. production of siderophores, antioxidants, enzymes, peptides, various secondary metabolites, and volatile organic compounds). Not all beneficial microorganisms exhibit the same mechanisms, posing a challenge to understanding their interaction with plants (Vejan et al. 2016).

Plant Growth-Promoting Rhizobacteria (PGPR) are notable for their multifunctional roles and the ability to enhance plant growth under conditions of both biotic (plant pathogens and pests) and abiotic (drought, nutrient deficiency, salinity, temperature, etc.) stresses. The direct mechanisms by which PGPR promote plant growth include the biosynthesis of phytohormones such as auxins, gibberellins (GAs), cytokinins (CKs), and nitric oxide (NO) and iron acquisition through siderophore production. Regarding the indirect mechanisms of growth promotion, PGPR mediate the biosynthesis of stress-responsive phytohormones, such as jasmonic acid (JA) and ethylene, induce systemic resistance (ISR), and produce antimicrobial compounds that mitigate the detrimental effects of phytopathogens on plant development (Cassán et al. 2014).

Auxins, one of the most well-known groups of phytohormones involved in growth regulation, are widely produced by various bacteria and yeasts. They play a crucial role in root development and cell elongation. Among the diverse types of active auxins such as indole-3-butyric acid (IBA), phenylacetic acid (PAA), and the precursor indole-3-acetonitrile (IAN), indole-3-acetic acid (IAA) stands out as the most extensively studied. Also, IAA can produce several benefits on plant growth by promoting wide range of plant growth traits, including both root and shoot growth, cell expansion, root bacterial colonization, defense against pathogens, stimulation of cell division, elongation of stems and roots, and loosening of root cell walls (Bhalerao et al. 2002). Approximately 80%–90% of characterized plant growth-promoting bacteria (PGPB) are capable of synthesizing IAA, emphasizing the importance of this phytohormone in the mechanisms employed by these bacteria to promote plant growth and development. IAA production by PGPB has been reported for many genera of bacteria, including *Acetobacter, Acinetobacter*, *Azospirillum*, *Arthrobacter*, *Azotobacter*, *Bacillus*, *Bradyrhizobium*, *Burkholderia*, *Herbaspirillum*, *Klebsiella*, *Mesorhizobium*, *Paenibacillus*, *Pantoea*, *Pseudomonas*, *Rhizobium*, *Rhodococcus*, *Serratia*, *Stenotrophomonas*, *Streptomyces*, and *Rouxiella* (Orozco-Mosqueda et al. 2023). In 2021, Embrapa, in collaboration with the Brazilian company Biotrop, developed PASTOMAX—a commercial inoculant designed for pasture systems based on *Brachiaria* grasses. This product line includes three formulations: PASTOMAX PK, containing *Pseudomonas fluorescens*; PASTOMAX N, containing *Azospirillum brasilense*; and PASTOMAX PROTEGE, a protective additive that enhances bacterial survival by shielding them from desiccation and solar radiation (Biotrop 2021). Both *Pseudomonas* and *Azospirillum* are genera of bacteria known to exhibit IAA production and biostimulation activity.

Humic and fulvic acids

Humic substance-based biostimulants—primarily humic acids and fulvic acids—can be defined as natural products present in soil organic matter, provided by the decomposition of plant and animal matter by microorganisms, as the main source of organic carbon. Humic acids (HA) are soluble in alkaline solution, precipitating when reaching pH 1–2, and fulvic acids (FA) remain in solution even after acidification (Canellas et al. 2015).

Humic substances can promote radicular changes physiologically and structurally through multiple interconnected mechanisms that directly enhance nutrient uptake and assimilation capabilities. Structurally, humic substances induce significant morphological modifications in root architecture, including enhanced lateral root formation and root hair development (Silva et al. 2024). Root hair development is particularly enhanced, with wheat seedlings showing 53%–94% increases in root hair length and increased density (Rathor et al. 2024), while pepper plants demonstrate enhanced root hair formation and thickness (Silva et al. 2024).

The enhanced nutrient uptake and assimilation resulting from these structural and physiological changes occurs through several mechanisms. The increased root surface area and biomass provide greater contact with soil nutrients, while the proliferation of root hairs dramatically expands the absorptive surface area available for nutrient acquisition (Nardi et al. 2016, Rathor et al. 2024). Additionally, humic substances enhance nutrient use efficiency by aiding the assimilation of both macro- and microelements, with effects on ion-specific channels and changes in charge balance of the cytosol or membrane fluidity and permeability (Nardi et al. 2016, Júnior et al. 2019).

Beyond these direct effects on root structure and physiology, humic substances significantly influence primary and secondary plant metabolism, contributing to improved resistance to abiotic stress and regulated plant growth. Proteomic analysis of maize roots revealed that humic acid treatment alters the expression of 34 proteins in root tissues, with significant changes occurring in energy metabolism pathways, including increased expression of protective proteins such as 2-cys peroxidase, putative VHS/GAT, and glutathione protein (Nunes et al. 2019). In terms of secondary metabolism, humic substances up-regulate genes encoding transcription factors involved in plant development and abiotic stress tolerance while down-regulating genes involved in secondary metabolic processes (Cha et al. 2021).

Protein hydrolysates

Protein hydrolysates (PHs) are mixtures of peptides and amino acids used as plant biostimulants obtained from enzymatic and chemical hydrolysis from agro-industrial residues, either of plant, like soy wastes (Calzoni et al. 2021), wheat gluten (He et al. 2019), and rice bran (Macias-Benitez et al. 2021), or animal origin, like fish waste (Madende and Hayes 2020) and chicken feathers (Genç and Atici 2019). These biostimulants can enhance crop quality parameters, nutrient efficiency, and abiotic stress tolerance. For example, some amino acids serve as precursors to plant hormones—tryptophan, for instance, is a precursor to auxin, which promotes root development. Others, such as proline and glycine-betaine, function as osmoprotectants, helping plants withstand stress conditions like drought and salinity (Colla et al. 2015, Lucini et al. 2015). Additionally, certain amino acids such as glycine, histidine, and phenylalanine chelate Fe^{3+}, Zn^{2+}, and Mn^{2+} in the soil solution, forming stable, water-soluble complexes that prevent micronutrient precipitation and improve availability at the root and soil interface. Integrating both soil and foliar delivery ensures comprehensive micronutrient nutrition, effectively correcting deficiencies and supporting optimal plant growth and stress resilience across various crops (Areche et al. 2023).

Seaweed extracts

Brown seaweeds are known and used for their properties of promoting plant growth, nutrient uptake, phytohormone-like activity, and their potential to improve resistance of crops to abiotic stresses, such as drought, salinity, and high temperatures. They are composed of a diverse array of chemical molecules, including complex polysaccharides, fatty acids, vitamins, phytohormones, and mineral nutrients. They can be applied on soils, in hydroponic solutions, or as foliar treatments (Battacharyya et al. 2015).

Seaweed extracts have demonstrated broad applicability across a wide range of plant species, including horticultural crops, fruit trees, ornamental plants, and floricultural species. Their use has been extensively reported in plants such as tomatoes, lettuce, potato, and maize, as well as in fruit crops like apples, bananas, and strawberries. In Basavaraja et al. (2018), seaweed extract from *K. alvarezii* and *G. edulis* was used as foliar spray on hybrid maize (*Zea mays* L.) crops increasing yield significantly by 18.54% and 26.04%, respectively. Also, the study reports a significant increase in the cob length and improvement of the macronutrient uptake (N, P, and K) of maize treated with seaweed foliar spray. Another study was conducted in which extracts derived from the marine algae *Ascophyllum nodosum* were applied to strawberry cultivars in field conditions and greenhouse. It improved berry yield, increased leaf area, shoot dry weights, root length, and root surface area (Alam et al. 2013). In soybean (*Glycine max* (L.) Merrill) cultivation, Repke et al. (2022) evaluated the foliar application of *Ascophyllum nodosum* seaweed extracts, and reported enhanced heat stress tolerance and CO_2 assimilation rates, while also improving overall productivity.

Chitosan and other biopolymers

Chitosan is a biopolymer that can be synthesized through industrial processes, but is also naturally occurring in various biological sources, including crustacean shells, insect exoskeletons, and fungal cell walls (Pichyangkura and Chadchawan 2015). Its structure consists of a chain of D-glucosamine and N-acetyl-D-glucosamine units, which are linked together by a glycosidic β (1–4) bond, being a deacetylated form of the biopolymer chitin (Du Jardin 2015, Sánchez-Machado et al. 2019).

Chitosan's versatility has facilitated its use as a component in various materials, including films, hydrogels, fibers, and micro- and nanoparticles. Chitosan applied through seed treatment and foliar spraying can enhance germination performance, stimulate early seedling development, promote root elongation and vegetative growth, contributing to increased crop yield, while inducing tolerance to abiotic stress, such as drought, salinity, and cold stress. Also, chitosan subunits are capable of binding to and interacting with various plant cellular components, including specific receptors involved in the activation of growth and defense-related gene expression. It induces systemic acquired resistance (SAR) and activates plant defense genes against pathogens, such as quitinase and glucanase. In addition to modulating the release of agrochemicals and facilitating the translocation of nanoparticles across cellular membranes, chitosan also plays a crucial role in regulating key defense-related enzymes, including superoxide dismutase, peroxidase, polyphenol oxidase, and phenylalanine ammonia-lyase. Through the activation of these enzymatic pathways, chitosan enhances the plant's oxidative stress response and secondary metabolite production, thereby strengthening resistance against fungal, bacterial, and viral pathogens (Jiménez-Arias et al. 2023, Iftime et al. 2024).

Organic fertilizers

Organic fertilizers are materials derived from organic sources (e.g. livestock manure, compost, vermicompost, bokashi, and sewage sludge) used as nutrient sources for the plants, enhancing soil health and fertility. These inputs improve the physical, chemical, and biological properties of soil by enhancing its structure, water retention, and aeration. They also serve as a source of essential nutrients, gradually releasing them to support plant growth. Furthermore, fertilizers stimulate microbial activity, promoting the proliferation of beneficial soil microorganisms (Bullor et al. 2024).

Various types of organic fertilizers can be produced depending on the biowaste material used as feedstock. Animal manure, which has been utilized for centuries, is a well-established organic fertilizer rich in essential nutrients such as nitrogen and phosphorus. Chicken manure has been evaluated for its ability to enhance soybean production in saline soils, where it demonstrated greater nutrient bioavailability, particularly of nitrogen (N), phosphorus (P), and potassium (K), compared to cattle manure and plant residues. Moreover, it proved effective in promoting soybean growth and increasing yield when compared to untreated controls (El-shaboury et al. 2024).

Similarly, sewage sludge waste contains significant amounts of nitrogen and phosphorus and can be employed in the formulation of biofertilizers; however, its application requires careful management due to the potential presence of harmful contaminants, such as heavy metals (Fijalkowski et al. 2017) and organic compounds as bisphenol A (Bolesta et al. 2022). In addition, composting of food waste by microorganisms and vermicomposting by earthworms represent sustainable alternatives for producing nutrient-rich organic fertilizers that contribute to soil health and fertility (Chew et al. 2019). Vermicompost application in lettuce cultivation has been shown to enhance productivity compared to conventional fertilization methods (Durak et al. 2017).

Another well-known organic fertilizer is bokashi. It is a type of fermented organic fertilizer produced through a process of aerobic semi-decomposition of organic waste mediated by chemoorganotrophic microorganisms under controlled oxygenated conditions. This process results in a partially stabilized material characterized by a slow nutrient release profile, which enhances soil fertility over time. Additionally, it contributes to soil health by introducing beneficial microbial communities and organic compounds that support plant development and nutrient cycling (Bullor et al. 2024). In a study involving tomato plants (*Lycopersicon esculentum* Mill.), the application of Bokashi significantly increased both plant height and leaf number compared to the untreated control. After eight weeks, while the control group reached a maximum height of less than 20 cm, the three Bokashi-treated groups exhibited plant heights exceeding 80 cm within the same period (Pohan et al. 2019).

Biological pest control bioinputs

Having discussed bioinputs that promote plant growth, we now turn to those that serve as biological pest control agents. Agricultural pests are organisms that cause harm to crops by causing damage, reducing yield or quality, or competing for resources. Here, we use the term agricultural pests to encompass a diverse range of taxonomic groups, including phytopathogenic fungi, herbivorous insects, plant-parasitic nematodes, invasive weeds, and detrimental invertebrates (i.e. formally plant pathogen and pests or biotic stress agents).

Biological pest control products are derived from living organisms or their byproducts, and act to suppress or manage pest populations through ecological interactions such as predation, parasitism, competition, or pathogenicity (Eilenberg et al. 2001). These products include macroorganisms (e.g. predatory insects, parasitoid wasps), microorganisms (e.g. entomopathogenic fungus *Beauveria bassiana*, entomopathogenic bacterium *Bacillus thuringiensis*), and semiochemicals (e.g. pheromones for mating disruption). Their mechanisms of action are species-specific and environmentally sustainable, reducing reliance on synthetic pesticides, while adhering to integrated pest management principles (Eilenberg et al. 2001, Lacey et al. 2015). Integrated pest management is a sustainable approach that promotes the use of a combination of strategies (e.g. biological control, traps, specific planting times, and crop rotation) to keep pest populations below economically damaging thresholds.

The efficacy of these agents is supported by their ability to target pests without disrupting non-target organisms, thereby preserving biodiversity, and enhancing agricultural resilience (Pretty and Bharucha 2015). Regulatory frameworks and scientific advancements continue to optimize their deployment, ensuring compatibility with global food security and ecological sustainability goals. The main classes of pest control agents used currently include biofungicides, bioinsecticides, bionematicides, semiochemicals, bioherbicides, and those used for biological control of invertebrates. These will be discussed next.

Biofungicides

Biofungicides are biocontrol agents formulated of living microorganisms or bioactive compounds derived from plants, fungi, or bacteria that suppress pathogenic fungi that are harmful to plants and may cause plant diseases (University of Connecticut 2023, Cenobio-Galindo et al. 2024). Table 2 presents a list of commercial biofungicides currently available on the market in Brazil from sources predominantly comprising *Bacillus spp*. and *Trichoderma spp.,* and plant extracts. They are continually gaining importance as eco-friendly alternatives to chemical fungicides to reduce important agricultural diseases, specifically in soybean, common bean, coffee, and vegetables.

The most prevalent biological agents documented are bacterial strains such as *Bacillus subtilis, Bacillus velezensis,* and *Bacillus pumilus*, and fungal strains of the genus *Trichoderma*. These microorganisms are well recognized for their numerous types of actions that include the production of antifungal metabolites, space occupation and competition for nutrients, parasitism of phytopathogenic fungi, and host plant systemic defense induction. Furthermore, plant-derived compounds can also be used as biofungicides, such as physcion, shown in Table 2, extracted from *Rheum palmatum*, which has demonstrated efficacy against a wide range of fungal phytopathogens, including *Alternaria solani*, the causal agent of black spot, *Colletotrichum lindemuthianum*, which induces anthracnose, and *Sphaerotheca fuliginea*, responsible for powdery mildew. The ability of these natural products to target multiple economically significant plant pathogens highlights the increasing diversification of compounds utilized in the development of biofungicides. The biofungicides discussed exhibit broad-spectrum activity, highlighting their potential as effective alternatives for the management of various plant diseases.

Soilborne pathogens like *Rhizoctonia solani* and *Sclerotinia sclerotiorum* are favorite targets, typically managed by *Trichoderma* and *Bacillus*-based products. The management of soil-borne pathogens such as *Rhizoctonia solani* and *Sclerotinia sclerotiorum* using *Trichoderma*- and *Bacillus*-based products represents a biocontrol approach that does not entirely eliminate the need for chemical fungicides, nor does it fully suppress disease occurrence. Studies have shown that these biocontrol agents provide variable levels of disease suppression. For example, *Bacillus velezensis* achieved 42.86%–67.78% control of cucumber wilt (Ta et al. 2024), while *Trichoderma* spp. reduced disease incidence in melon by 28.00%–69.33% (Almeida et al. 2024). Effective disease management can be obtained through integrated strategies that combine biological agents with reduced doses of chemical fungicides. Notably, studies have demonstrated that the combination of *Trichoderma* with half the recommended dose of azoxystrobin was as effective as the full fungicide dose alone (Schierling et al. 2024).

Products composed of *Trichoderma harzianum* antagonizes fungal pathogens via mycoparasitism, secreting chitinases and glucanases to degrade cell walls, while concurrently competing for nutrients and space (Harman et al. 2004). The ones composed of *Bacillus subtilis* produce lipopeptides (e.g. iturin, surfactin) and polyketides with broad-spectrum antifungal activity, disrupting membrane integrity and spore germination (Cawoy et al. 2015).

The endophytic fungus *Muscodor albus*, isolated from *Cinnamomum zeylanicum* (cinnamon), produces volatile organic compounds (VOCs)—including alcohols, esters, ketones, acids, and lipids—that act synergistically to lethally suppress phytopathogenic fungi and bacteria. While individual compounds lack biocidal activity, their combined interaction, termed “mycofumigation,” demonstrates broad-spectrum antimicrobial efficacy. Esters, particularly 3-methyl-

Table 2. Examples of biofungicides commercially available in Brazil.

Commercial name	Company	Developer	Composition	Class	Launch tear	Country	Action	Recommended uses	Website
BIOMAGNO; BIOHARMER	TOTAL BIOTECNOLOGIA	Tacto Biotecnologia and TOTAL BIOTECNOLOGIA	*Bacillus amyloliquefaciens* isolate CNPSo3202, *Bacillus velezensis* isolate CNPSo3602, *Bacillus thuringiensis* isolate CNPSo3915	Biofungicide; Bionematicide	—	Brazil	Controls lesion nematode (*Pratylenchus brachyurus*), cyst nematode (*Heterodera glycines*), root-knot nematodes (*Meloidogyne incognita*, *M. javanica*, *M. exigua*), reniform nematode (*Rotylenchulus reniformis*), and damping-off (*Rhizoctonia solani*).	Seed treatment, furrow application, or drench application (depending on target)	https://biotrop.com.br/produto/biomagno/
Biotrix	TOYOBO Biological Products	Embrapa rice and beans (in partnership with other companies)	*Trichoderma harzianum*	Biofungicide	2024	Brazil	Controls white mold (*Sclerotinia sclerotiorum*), gray stem rot, and *rhizoctoniosis*.	Ground application via foliar spray	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/12388/produto-biologico-a-base-de-trichoderma-sp-para-controle-de-doencas-radiculares
BOMBARDEIRO	Biotrop	Tacto Biotecnologia and TOTAL BIOTECNOLOGIA	*Bacillus subtilis* isolate CCTB04, *Bacillus velezensis* isolate CCTB09, *Bacillus pumilus* isolate CCTB05	Biofungicide	—	Brazil	Controls brown spot (*Septoria glycines*).	Foliar application in all crops with target presence	https://biotrop.com.br/produto/bombardeiro/
Caravan	Koppert Brasil	Multiple companies	*Bacillus pumilus* isolate CNPSo 3203	Biofungicide	—	Brazil	Controls brown spot (*Septoria glycines*), target spot (*Corynespora cassiicola*), anthracnose (*Colletotrichum lindemuthianum*), ramularia (*Ramularia areola*), coffee rust (*Hemileia vastatrix*), and	Foliar or aerial application in all crops	https://www.koppert.com.br/caravan/

Table 2. Continued

Commercial name	Company	Developer	Composition	Class	Launch tear	Country	Action	Recommended uses	Website
							other fungal diseases.		
FRONTIER CONTROL	Simbiose	Bioma Indústria	*Bacillus velezensis* strain Labim 40	Biofungicide	—	Brazil	Controls brown spot (*Septoria glycines*) and bacterial pale spot (*Pantoea ananatis*).	Foliar application in all crops	https://simbiose-agro.com.br/produto/frontiercontrol/
FURATROP; NEMATROP; Biotrinsic Nemafree; Submax	TOTAL BIOTECNOLOGIA	Tacto Biotecnologia and TOTAL BIOTECNOLOGIA	*Bacillus subtilis* isolate CNPSo 2657	Biofungicide; Bionematicide	—	Brazil	Controls white mold (*Sclerotinia sclerotiorum*), root-knot nematode (*Meloidogyne javanica, M. incognita*), lesion nematode (*Pratylenchus brachyurus*), cyst nematode (*Heterodera glycines*), and damping-off (*Rhizoctonia solani*).	Furrow application, seed treatment, or foliar spray (depending on target)	https://biotrop.com.br/produto/furatrop/
Habitat	Bionat Soluções Biológicas	Embrapa Genetic Resources (in partnership with other companies)	*Trichoderma afroharzianum*	Biofungicide	2022	Brazil	Controls root rot (*Rhizoctonia solani*) and white mold (*Sclerotinia sclerotiorum*).	Seed application for root rot control; soil application for white mold control. Effective in soybeans but applicable to all crops with fungal presence	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/12251/biofungicida-a-base-de-trichoderma-para-o-controle-da-podridao-radicular-rhizoctonia-solani-e-do-mofo-branco-sclerotinia-sclerotiorum
LALSTOP ORGANIC DS	Lallemand Soluções Biológicas	Lallemand Soluções Biológicas	*Trichoderma asperellum* isolate URM 5911	Biofungicide	—	Brazil	Controls *Rhizoctonia solani* and *Fusarium solani* f. sp. phaseoli	Seed treatment in all crops	https://www.lallemandplantcare.com/pt-br/brasil/produtos/produto-detalhes/lalstop-organic-ds/?type=biofungicida

Table 2. Continued

Commercial name	Company	Developer	Composition	Class	Launch tear	Country	Action	Recommended uses	Website
NEMACON-TROL	Simbiose	Simbiose	*Bacillus amyloliquefaciens* isolate SIMBI BS 10	Biofungicide; Bionematicide	—	Brazil	Controls soybean cyst nematode (*Heterodera glycines*), root-knot nematodes (*Meloidogyne exigua, M. incognita*), and white mold (*Sclerotinia sclerotiorum*).	Seed treatment, furrow application, or foliar spray	https://simbiose-agro.com.br/produto/nemacontrol/
Physcion	Dinagro	Inner Mongolia Kingbo Biotech	Extract of *Rheum palmatum L.*	Biofungicide	—	Brazil	Controls black spot (*Alternaria solani*), anthracnose (*Colletotrichum lindemuthianum*), powdery mildew (*Sphaerotheca fuliginea*).	Foliar application in over 50 registered crops	https://www.naterra.com.br/physcion-fungicida-20-lts---4 × 5l-141/p?idsku=141&gad_source=1&gclid=Cj0KCQjwqcO_BhDaARIsACz62vM_uIFruNGpniNl-Nia05Jgu_t56_dgVfUttlxjOeDBWGEuXzixkSIaAqQMEALw_wcB
PROVILAR	FMC Química do Brasil	Chr. Hansen GmbH, Cheminova Deutschland, FMC	*Bacillus velezensis* strain RTI301 and *Bacillus subtilis* strain RTI477	Biofungicide	—	Brazil	Controls white mold (*Sclerotinia sclerotiorum*) and target spot (*Corynespora cassiicola*).	Foliar application in all crops	https://www.fmcagricola.com.br/provilar/# https://www.fmcagricola.com.br/Content/Fotos/Bula%20-%20Provilar.pdf
Serenade	Bayer	Bayer México	*Bacillus subtilis* strain QST 713	Biofungicide; Bionematicide; Bactericide	—	Brazil	Controls *Botrytis cinerea, Fusarium oxysporum, Rhizoctonia solani, anthomonas citri*, and other pathogens.	Variable application methods depending on crop	https://www.agro.bayer.com.br/d/fungicida-bcs-serenade-br

Table 2. Continued

Commercial name	Company	Developer	Composition	Class	Launch tear	Country	Action	Recommended uses	Website
Trichodermil SC 1306	Koppert Brasil	Koppert BV, Biotech Controle Biológico	*Trichoderma harzianum* strain ESALQ-1306	Biofungicide; Bionematicide	—	Brazil	Controls dry root rot (*Fusarium solani* f.sp. *phaseoli*), root rot (*Rhizoctonia solani*), soybean stem rot (*Sclerotinia sclerotiorum*), and lesion nematode (*Pratylenchus zeae*).	Furrow spray or total-area spray	https://www.koppert.com.br/trichodermil/
TRITTER	NOOA Agricultural Science and Technology; Ballagro Agro Tecnologia	NOOA Agricultural Science and Technology; Ballagro Agro Tecnologia	*Trichoderma harzianum* isolate IBLF006	Biofungicide	2018	Brazil	Controls water rot (*Rhizoctonia solani*) and white mold (*Sclerotinia sclerotiorum*).	Furrow application during sowing (beans); foliar application (lettuce and soybeans)	https://www.nooabrasil.com.br/tritter

1-butanol acetate, exhibit the highest inhibitory potency. This natural mechanism offers a sustainable alternative to synthetic fungicides, highlighting its potential for eco-friendly agricultural disease management (Strobel et al. 2001).

One of the first controlled studies to evaluate the efficacy of *Muscodor albus* against *Phytophthora capsica*, the causal agent of root and stem rot in sweet pepper and butternut squash, was conducted under greenhouse conditions using pathogen-infested substrate treated with three concentrations of *M. albus*, mefenoxam, or left untreated. The highest concentration of *M. albus* led to a modest but statistically significant reduction in disease severity across four pepper cultivars (i.e. *Alliance*, *Aristotle*, *Paladin*, and *Revolution*) compared to the pathogen-only control. Only the cultivar *Paladin*, which is inherently more tolerant, exhibited disease suppression to commercially acceptable levels (Camp et al. 2008).

Another interesting study evaluated the potential application of *Muscodor albus* biofungicidal activity through its volatile organic compounds (VOCs) in storage, for preventing the contamination of grains. Conidia of seven mycotoxin-producing fungi (i.e. *Aspergillus carbonarius*, *A. flavus*, *A. niger*, *A. ochraceus*, *Penicillium verrucosum*, *Fusarium culmorum*, and *F. graminearum*) were exposed to VOCs released from *M. albus*-colonized rye grain (2 g/L headspace) in sealed containers at 20°C for 24 hours. Interestingly, this treatment resulted in complete inhibition of conidial germination or total mortality across all tested species (Braun et al. 2012).

Bioinsecticides

Bioinsecticides, defined as pest control agents derived from naturally occurring organisms or their bioactive compounds, encompass entomopathogenic bacteria, fungi, viruses, protozoa and nematodes, which suppress insect populations through infection, toxin production, or parasitism (Glare et al. 2012).

Table 3 shows an overview of commercially used bioinsecticides in Brazil, which are primarily microbial compounds such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and some baculoviruses, along with phytochemical-based products. The bioinsecticides target a broad range of economically important pests, from lepidopteran larvae to whiteflies, stink bugs, and weevils. Application methods vary with the pest and crop type, with the most common being foliar sprays augmented by soil application, aerial applications, and fertigation as required. Some of these are lepidopteran-only targeted products such as Agree and Dipel WG, while others such as Boveril and BIOOLIMPO direct their range of activity to hemipterans and coleopterans.

The products present different modes of action, the ones based on *Bacillus thuringiensis* commercialized as Dipel and Agree, Bt strains produce Cry toxins that disrupt insect midgut membranes, effectively targeting lepidopteran pests in soybean, maize, and cotton crops (Ragasruthi et al. 2024). Others based on *Beauveria bassiana* such as Boveril and Bovemip, infect pests such as whiteflies (*Bemisia tabaci*), weevils, scarabs, thrips, and aphids via cuticle penetration and mycosis (Faria and Wraight 2007). *Beauveria* infects insects by adhering to the cuticle, penetrating through vulnerable regions using mechanical and enzymatic mechanisms, and proliferating in the hemolymph while suppressing the host's immune responses. The fungus produces toxins, ultimately leading to the insect's death, followed by sporulation under favorable environmen-

Table 3. Examples of bioinsecticides commercially available in Brazil.

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
Agree	Bio Controle	Certis USA	*Bacillus thuringiensis* subsp. *aizawai* GC 91 hybrid	Bioinsecticide	—	Brazil	Controls *Bonagota salubricola*, *Cryptoblabes gnidiella*, *Diaphania hyalinata*, *Helicoverpa armigera*, *Plutella xylostella*, *Spodoptera frugiperda*, and *Tuta absoluta*.	Spray application in all crops	https://biocontrole.com.br/produto/agree/
Bettus org	NOOA Agricultural Science and Technology	NOOA Agricultural Science and Technology	*Bacillus thuringiensis* var. *kurstaki* isolate HD-1 (S1450)	Bioinsecticide	2021	Brazil	Acts via ingestion, disrupting digestive membranes of lepidopteran larvae.	Spray applications on all plants	https://www.nooabrasil.com.br/bettus
BIOCASH	TOTAL BIOTECNOLOGIA	TOTAL BIOTECNOLOGIA	*Spodoptera frugiperda* multiple *nucleopolyhedrovirus*, SfMNPV	Bioinsecticide	—	Brazil	Controls *Spodoptera frugiperda* (fall armyworm).	Foliar application in all crops with target presence	https://biotrop.com.br/produto/biocash/
BIOEXOS PLUS	TOTAL BIOTECNOLOGIA	TOTAL BIOTECNOLOGIA	Extract of *Azadirachta indica*	Bioinsecticide	—	Brazil	Controls *Tetranychus urticae* (spider mite), *Deois flavopicta* (pasture spittlebug), *Dalbulus maidis* (corn leafhopper), *Chrysodeixis includens* (false armyworm), *Spodoptera frugiperda* (fall armyworm), *Bemisia tabaci* (whitefly), *Euschistus heros* (brown stink bug), *Plutella xylostella* (diamondback moth), *Tuta absoluta* (tomato leafminer), and *Frankliniella schultzei* (thrips).	Foliar application in cotton, coffee, sugarcane, citrus, beans, corn, pastures, peppers, cabbage, soybeans, tomatoes, and wheat	https://biotrop.com.br/produto/bioexos/
BIOOLIMPO	TOTAL BIOTECNOLOGIA	TOTAL BIOTECNOLOGIA	*Beauveria bassiana* isolate IBCB 66 and *Metarhizium anisopliae* isolate IBCB 425	Bioinsecticide	—	Brazil	Controls *Deois flavopicta* (pasture spittlebug) and *Euschistus heros* (brown stink bug).	Foliar application in all crops	https://biotrop.com.br/produto/bioolimpo/

Table 3. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
Bovemip	PROMIP	PROMIP	*Beauveria bassiana* strain IBCB 66	Bioinsecticide	—	Brazil	Controls *Bemisia tabaci* race B (whitefly), *Cosmopolites sordidus* (banana weevil), *Tetranychus urticae* (spider mite), *Dalbulus maidis* (corn leafhopper), and *Sphenophorus levis* (sugarcane weevil).	Foliar application in all crops	https://promip.agr.br/bovemip/#:~:text=BoveMip%C2%AE%20%C3%A9%20um%20inseticida%20e%20acaricida%20biol%C3%B3gico%20composto%20pelo,apresentando%20a%C3%A7%C3%A3o%20sobre%20a%20cultura.
Boveril	Koppert Brasil	Multiple companies	*Beauveria bassiana* strain ESALQ PL63	Bioinsecticide	—	Brazil	Controls *Hypothenemus hampei* (coffee berry borer), *Bemisia tabaci* (whitefly), *Sphenophorus levis* (sugarcane weevil), *Planococcus minor* (mealybug), *Tetranychus urticae* (spider mite), *Thaumastocoris peregrinus* (bronze bug), *Glycaspis brimblecombei* (red gum lerp psyllid), and *Gonipterus scutellatus* (eucalyptus weevil).	Ground, aerial, or dust application	https://www.koppert.com.br/boveril-evo/
Bovettus org	NOOA Agricultural Science and Technology	NOOA Agricultural Science and Technology	*Beauveria bassiana* isolate IBCB 66	Bioinsecticide; Bioacaricide	2020	Brazil	Controls *Bemisia tabaci* race B (whitefly), *Cosmopolites sordidus* (banana weevil), *Tetranychus urticae* (spider mite), *Dalbulus maidis* (corn leafhopper), and *Sphenophorus levis* (sugarcane weevil).	Spray application on all crops	https://www.nooabrasil.com.br/bovettus
Dipel WG	Sumitomo Chemical Brasil	Sumitomo Chemical Brasil	*Bacillus thuringiensis* var. *kurstaki*, strain HD-1	Bioinsecticide	—	Brazil	Controls a broad spectrum of lepidopteran larvae.	Foliar application in all crops	https://www.sumitomochemical.com.br/produtos/inseticidas-biologicos/dipel-wg/

Table 3. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
LALGUARD JAVA	Lallemand Soluções Biológicas	Embrapa Rice and Beans (in partnership with other companies)	*Cordyceps javanica*	Bioinsecticide	2023	Brazil	Controls *Bemisia tabaci* (whitefly).	Terrestrial application using a foliar sprayer	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/11043/cordyceps-javanica-based-bioinsecticide-for-whitefly-biological-control
Lepthure	Bionat Soluções Biológicas	Embrapa Genetic Resources (in partnership with other companies)	*Bacillus thuringiensis* strain S234	Bioinsecticide	2022	Brazil	Controls *Anticarsia gemmatalis* (soybean caterpillar), *Chrysodeixis includens* (false armyworm), and *Spodoptera frugiperda* (fall armyworm).	Foliar application in soybean and corn crops; adaptable to other crops	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/11182/biopesticida-contendo-estirpe-de-bacillus-thuringiensis-toxica-a-lagartas https://essere.group/bionat/
Mettus org	NOOA Agricultural Science and Technology	NOOA Agricultural Science and Technology	*Metarhizium anisopliae* isolate IBCB 425	Bioinsecticide	2020	Brazil	Controls *Mahanarva fimbriolata* (root spittlebug), *Zulia entreriana* (pasture spittlebug), and *Deois avopicta* (pasture spittlebug).	Spray application on all crops	https://www.nooabrasil.com.br/mettus
Nematec	Embrapa Florestas	Embrapa Florestas (in partnership with other companies)	*Deladenus siricidicola*	Bioinsecticide	1989	Brazil	Controls *Sirex noctilio* (woodwasp), a pest affecting pine plantations.	Application via drench or fertigation	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/5235/nematec
Spodovir, VirControl S.f, Looper Protection, CartuchoVIT, Vircontrol C.i, Laphy Protection, Spodovir plus, Baculomip, VirControl H.a.	Simbiose, Bioma Indústria, Andermatt, Promip	Embrapa Maize and Sorghum (in partnership with other companies)	Baculovirus-based	Bioinsecticide	2017	Brazil	Insecticide for various crop pests.	Application method varies by product version (powder or liquid formulations)	https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/11033/bioinseticidas-a-base-de-baculovirus-para-o-controle-de-lagartas

tal conditions. The infection duration varies depending on the host species and environmental factors (Zimmermann 2007).

Bionematicides

Bionematicides are biocontrol agents derived from microorganisms (e.g. fungi, bacteria) or their bioactive metabolites, which suppress plant-parasitic nematodes through mechanisms such as parasitism, degradation of nematode cuticles, or toxic compounds production (Wolfgang et al. 2019).

Table 4 presents commercially available bionematicides in Brazil. Several biological nematicides have been launched in Brazil, mostly based on *Bacillus* species, following the global trend for sustainable nematode control. Products such as AUBA (*Bacillus amyloliquefaciens* CN-307) and various formulations by TOTAL BIOTECNOLOGIA (e.g. BIOMAGNO, BIOHARMER, FURATROP, NEMATROP) reflect the growing use of beneficial bacteria for the control of key nematode pests such as *Meloidogyne incognita, Heterodera glycines*, and *Pratylenchus brachyurus*.

These bionematicides possess versatile application methods, including seed treatment, furrow spray, and drenching, making them more compatible with integrated pest management programs. Their double action against both nematodes and soil-dwelling pathogens like *Rhizoctonia solani* also makes them promising for enhancing plant health with reduced chemical inputs.

Products based on the fungus *Purpureocillium lilacinum*, such as NEMAT STELLUS (Ballagro Agro Tecnologia Ltda.), act by parasitizing nematode eggs and females through the production of chitinases and proteases, effectively controlling *Meloidogyne* spp. in different crops (Rigobelo et al. 2024). Comparative studies showed that *Purpureocillium lilacinum* bionematicide applications alone or combined with bromelain compost were more effective than the chemical nematicide carbofuran in controlling *Meloidogyne* spp., achieving superior plant growth promotion and reduced root damage intensity (Swibawa et al. 2024).

Similarly, formulations containing *Bacillus firmus*, such as in VOTIVO PRIME (BASF S.A.), exert nematicidal activity by secreting lipopeptides and volatile organic compounds (VOCs) that impair nematode chemotaxis and juvenile mobility. In addition, *B. firmus* produces lytic enzymes, including chitinases and proteases, which degrade nematode eggshells and cuticles, thereby reducing egg viability (Vasantha-Srinivasan et al. 2024). Field and greenhouse studies have demonstrated the comparative efficacy of bionematicides versus chemical nematicides in managing root-knot nematodes. In controlled trials with tomato plants infested with *Meloidogyne incognita*, *Bacillus firmus* formulations (BioNem) applied at 200–400 $kg.ha^{-1}$ reduced gall formation by 75%–84% and increased plant height by 29%–31% compared to untreated controls (Terefe et al. 2009).

Semiochemicals

Semiochemicals are chemical compounds produced by microorganisms, animals, and plants that mediate communication and interactions within and between species. They regulate intraspecific interactions (pheromones) and interspecific interactions (allelochemicals).

Interactions are mediated by the emission of chemical signals by one organism and their reception by another, either of the same species or a different one. Semiochemicals are typically volatile organic compounds containing between 10 and 25 carbon atoms, and may exhibit saturated or unsaturated, cyclic, or acyclic structures, commonly featuring aldehyde, alcohol, or acetate functional groups.

Pheromones encompass various types with distinct biological functions; among these, sexual and aggregation pheromones are the most extensively studied. Allelochemicals are classified into three categories based on which organism benefits from the interaction: (a) allomone, when the emitter gains the advantage; (b) kairomone, when the receiver benefits; and (c) synomone, when both organisms benefit.

Fungi, bacteria, and nematodes produce both pheromones and allelochemicals. In addition to mediating intraspecific interactions, these compounds also facilitate interspecific communication—fungi and bacteria with insects and plants, and nematodes primarily with plants (Magalhães et al. 2020).

In integrated pest management (IPM), interventions aimed at eliminating target insect populations are applied judiciously and only when necessary. Typically, IPM employs a combination of complementary strategies, including the use of resistant crop varieties, pheromone-based monitoring, application of selective agrochemicals, deployment of genetically modified plants, release of natural predators or parasitoids, and the use of entomopathogenic microorganisms that cause disease in insect pests.

Pheromone-based strategies in integrated pest management can be deployed through different approaches, contingent upon the plant's developmental stage and the infestation intensity of the target pest. Applications include monitoring, mass trapping, and mating disruption. Given that only minute quantities of pheromones are required, this method represents a highly attractive alternative, exerting minimal impact on non-target organisms and leaving no detectable residues in the environment or agricultural products (Mozer 2023).

Data from the Agricultural Pesticide Information System (AGROFIT) of the Brazilian Ministry of Agriculture and Livestock indicate the registration of 49 pheromone-based products for agricultural use. Among these, 21 are designated for soybean cultivation, 21 for maize, 25 for cotton, 21 for sugarcane, 20 for coffee, 22 for citrus crops, 20 for rice, and 21 for cereals such as wheat and sorghum. These products are available in diverse formulations, including rubber septa, encapsulated suspensions, lures, powders, and pastes, reflecting the broad applicability and versatility of pheromone technology across major crop systems (MAPA 2025a).

The fall armyworm (*Spodoptera frugiperda*), a major pest affecting multiple crops such as maize, rice, and sugarcane, has seen the registration of three new pheromone-based products in recent years. Similarly, *Anthonomus grandis*, a key pest of cotton, now has two additional products available for its management. Furthermore, new pheromone products have been developed for fruit crops (grape and strawberry), vegetables (carrot), and leafy greens (lettuce), expanding the applicability of semiochemical-based strategies across diverse agricultural systems.

Bento et al. (2016) conducted a cost–benefit analysis applied to the citrus industry in the state of São Paulo, Brazil, over the period from 2001 to 2013, evaluating the use of pheromone-baited traps targeting the citrus fruit borer (*Gymnandrosoma aurantianum*) in monitored areas. The total losses averted through the adoption of pheromone-baited traps ranged from USD 132.7 million to USD 1.32 billion in gross revenue.

Table 4. Examples of bionematicides commercially available in Brazil.

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
AUBA	NOOA Agricultural Science and Technology	NOOA Agricultural Science and Technology	*Bacillus amyloliquefaciens* strain CN-307	Bionematicide	2023	Brazil	Controls root-knot nematode (*Meloidogyne incognita*), cyst nematode (*Heterodera glycines*), and lesion nematode (*Pratylenchus brachyurus*).	Spray application in planting furrows	https://www.nooabrasil.com.br/auba
BIOMAGNO; BIOHARMER	TOTAL BIOTECNOLOGIA	Tacto Biotecnologia and TOTAL BIOTECNOLOGIA	*Bacillus amyloliquefaciens* isolate CNPSo3202, *Bacillus velezensis* isolate CNPSo3602, *Bacillus thuringiensis* isolate CNPSo3915	Biofungicide; Bionematicide	—	Brazil	Controls lesion nematode (*Pratylenchus brachyurus*), cyst nematode (*Heterodera glycines*), root-knot nematodes (*Meloidogyne incognita, M. javanica, M. exigua*), reniform nematode (*Rotylenchulus reniformis*), and damping-off (*Rhizoctonia solani*).	Seed treatment, furrow application, or drench application (depending on target)	https://biotrop.com.br/produto/biomagno/
FURATROP; NEMATROP; biotrinsic nemafree; Submax	TOTAL BIOTECNOLOGIA	Tacto Biotecnologia and TOTAL BIOTECNOLOGIA	*Bacillus subtilis* isolate CNPSo 2657	Biofungicide; Bionematicide	—	Brazil	Controls white mold (*Sclerotinia sclerotiorum*), root-knot nematode (*Meloidogyne javanica, M. incognita*), lesion nematode (*Pratylenchus brachyurus*), cyst nematode (*Heterodera glycines*), and damping-off (*Rhizoctonia solani*).	Furrow application, seed treatment, or foliar spray (depending on target)	https://biotrop.com.br/produto/furatrop/
LALNIX RESIST	Lallemand Soluções Biológicas	Lallemand Soluções Biológicas	*Trichoderma koningiopsis* IBCB 56/12	Bionematicide	—	Brazil	Controls soybean cyst nematode (*Heterodera glycines*), root-knot nematode (*Meloidogyne incognita*), and lesion nematode (*Pratylenchus brachyurus*).	Seed treatment in all crops	https://www.lallemandplantcare.com/pt-br/brasil/produtos/produto-detalhes/lalnix-resist/?type=protecao-cultivos

Table 4. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
NEMACON-TROL	Simbiose	Simbiose	*Bacillus amyloliquefaciens* isolate SIMBI BS 10	Biofungicide; Bionematicide	—	Brazil	Controls soybean cyst nematode (*Heterodera glycines*), root-knot nematodes (*Meloidogyne exigua, M. incognita*), and white mold (*Sclerotinia sclerotiorum*).	Seed treatment, furrow application, or foliar spray	https://simbiose-agro.com.br/produto/nemacontrol/
NEMAT STELLUS	Ballagro Agro Tecnologia	Ballagro Agro Tecnologia	*Purpureocillium lilacinum* [syn. *Paecilomyces lilacinus*] strain URM 7661 and *Pochonia chlamydosporia* strain URM 8121	Bionematicide	—	Brazil	Controls root-knot nematodes (*Meloidogyne javanica, M. incognita*), reniform nematode (*Rotylenchulus reniformis*), and lesion nematode (*Pratylenchus brachyurus*).	Seed treatment or furrow application	https://ballagro.com.br/produtos/protecaodeplantas/nemat-stellus/
Onix OG	Lallemand Soluções Biológicas	Lallemand Soluções Biológicas	*Bacillus methylotrophicus* UFPEDA 20	Bionematicide	—	Brazil	Controls root-knot nematode (*Meloidogyne javanica*) and lesion nematode (*Pratylenchus brachyurus*).	Seed treatment or terrestrial application	https://www.lallemandplantcare.com/pt-br/brasil/produtos/produto-detalhes/onix-og/?type=protecao-cultivos
PRESENCE FLEX; PRESENCE FULL; KALIVAR	FMC Química do Brasil	Chr. Hansen GmbH and FMC	*Bacillus subtilis* strain FMCH002 [DSM32155] and *Bacillus licheniformis* strain FMCH001 [DSM32154])	Bionematicide	—	Brazil	Controls lesion nematode (*Pratylenchus brachyurus*), root-knot nematodes (*Meloidogyne graminicola, M. incognita, M. javanica*), and cyst nematode (*Heterodera glycines*).	Furrow application, base plant spray, or seed treatment	https://www.fmcagricola.com.br/Produtos/DetalhesProdutos/95
QUARTZO; SURFACE	FMC Química do Brasil	FMC Química do Brasil	*Bacillus subtilis* strain FMCH002 and *Bacillus licheniformis* strain FMCH001	Bionematicide	—	Brazil	Controls lesion nematode (*Pratylenchus brachyurus*), root-knot nematodes (*Meloidogyne graminicola, M. incognita, M. javanica*),	Furrow application or base plant spray	https://www.fmcagricola.com.br/Produtos/DetalhesProdutos/55

Table 4. Continued

Commercial name	Company	Developer	Composition	Class	Launch year	Country	Action	Recommended uses	Website
							and cyst nematode (*Heterodera glycines*).		
Rizos OG	Lallemand Soluções Biológicas	Lallemand Soluções Biológicas	*Bacillus subtilis* UFPEDA 764	Bionematicide	—	Brazil	Controls root-knot nematode (*Meloidogyne javanica*) and lesion nematode (*Pratylenchus brachyurus*).	Seed treatment or terrestrial application	https://www.lallemandplantcare.com/pt-br/brasil/produtos/produto-detalhes/rizos-og/?type=protecao-cultivos
ROVISA; ROVISAR BR	FMC Química do Brasil	FMC Química do Brasil	*Bacillus thuringiensis* strain RTI545	Bionematicide	—	Brazil	Controls reniform nematode (*Rotylenchulus reniformis*) and cyst nematode (*Heterodera glycines*).	Terrestrial application, seed treatment, or rhizosphere application	https://www.fmcagricola.com.br/Produtos/DetalhesProdutos/108
Serenade	Bayer	Bayer México	*Bacillus subtilis* strain QST 713	Biofungicide; Bionematicide; Bactericide	—	Brazil	Controls *Botrytis cinerea*, *Fusarium oxysporum*, *Rhizoctonia solani*, *Xanthomonas citri*, and other pathogens.	Variable application methods depending on crop	https://www.agro.bayer.com.br/d/fungicida-bcs-serenade-br
Trichodermil SC 1306	Koppert Brasil	Koppert BV, Biotech Controle Biológico	*Trichoderma harzianum* strain ESALQ-1306	Biofungicide; Bionematicide	—	Brazil	Controls dry root rot (*Fusarium solani* f.sp. *phaseoli*), root rot (*Rhizoctonia solani*), soybean stem rot (*Sclerotinia sclerotiorum*), and lesion nematode (*Pratylenchus zeae*).	Furrow spray or total-area spray	https://www.koppert.com.br/trichodermil/
VOTIVO PRIME	BASF	BASF, Bayer, TOTAL BIOTECNOLOGIA	*Bacillus firmus* strain I-1582	Bionematicide	—	Brazil	Controls *Heterodera glycines*, *Meloidogyne graminicola*, *Rotylenchulus reniformis*, and *Pratylenchus brachyurus*.	Seed treatment or furrow application	https://agriculture.basf.com/br/pt/protecao-de-cultivos-e-sementes/produtos/votivo-prime-basf-tratamento-de-sementes-de-soja

Despite the increase in the number of registered products with the Brazilian Ministry of Agriculture and Livestock (MAPA), the primary pests of soybean, whose pheromones have already been identified, still lack commercially available pheromone formulations. Similarly, maize—the second most important crop in Brazil—as well as rice and sugarcane, continue to be affected by pests for which pheromones have yet to be identified.

Bioherbicides

Bioherbicides are biologically derived agents for weed suppression, encompassing microorganisms (e.g. fungi, bacteria), plant-derived allelochemicals, or microbial metabolites that inhibit weed growth through mechanisms such as phytotoxin production, enzymatic inhibition, or competition (Duke et al. 2022). To date, there are no bioherbicide products registered with the Ministry of Agriculture, Livestock and Food Supply (MAPA 2025b).

One obvious major challenge of developing effective bioherbicides is the potential for unintended effects on non-target plant species, particularly crop plants. Although narrow selectivity toward the target weed is a desirable characteristic, this same specificity can limit the bioherbicide's range of application, thus negatively impacting its commercial viability. However, in specific agricultural systems where a single target weed is predominant and crop sensitivity is low, bioherbicides may offer a sustainable weed management solution.

In the scientific literature there are reports showing the potential of bioherbicides. For instance, *Phoma macrostoma* 94–44B induces foliar photobleaching and necrosis in susceptible plants through the production of macrocidins, showing effective control of dandelion and other broadleaved weeds under field conditions (Evans et al. 2013).

The bioherbicide *Colletotrichum gloeosporioides* f. sp. *aeschynomene* (CGA) has shown effective control of leguminous weeds through formulation strategies that enhance spore infectivity. In greenhouse trials, aqueous suspensions of CGA caused 98%–100% mortality of *Aeschynomene virginica* seedlings within 15 days. Inverted emulsion formulations and those containing the surfactant Silwet L-77, both with CGA, achieved 100% mortality and significantly reduced biomass and plant height across *A. virginica*, *A. indica*, and *Sesbania exaltata*. Additionally, formulation modifications have expanded CGA's host range, enabling control of previously unaffected species, thereby reinforcing its potential for integrated weed management in cropping systems such as rice and soybean (Boyette et al. 2019).

Biological control with invertebrates

Biological pest control with invertebrates entails the strategic utilization of natural antagonists—including predators (e.g. lady beetles, lacewings), parasitoids (e.g. *Trichogramma* wasps), and entomopathogenic nematodes (e.g. *Steinernema* spp.)—to suppress pest populations through mechanisms such as predation, parasitism, or symbiotic pathogenicity. These agents target specific pest life stages (e.g. eggs, larvae, adults), disrupting pest life cycles while minimizing non-target impacts (van Lenteren et al. 2018).

Among parasitoids products used in Brazil are those based on the *Trichogramma* genera, such as TrichoMip-P (Promip), which are egg-parasitoid wasps widely employed in biological control programs to suppress lepidopteran pests. These parasitoids exhibit a host-specific lifecycle, wherein females locate pest eggs using chemical cues (kairomones) emitted by host scales or oviposition fluids. Upon locating a suitable host egg, the female *Trichogramma* deposits its eggs inside it. The developing larvae consumes the host's egg from inside, and emerge as adults, leaving the host egg non-viable (Smith 1996).

Another well-established example of invertebrate-mediated biological control also found in sugarcane cultivation occurs when the larval parasitoid *Cotesia flavipes* (Hymenoptera: Braconidae) targets the sugarcane borer *Diatraea saccharalis*. Since its introduction into Brazilian cane fields, *C. flavipes* has been mass-reared and released over more than 1.7 million hectares, resulting in sustained reductions in borer infestation levels and significant improvements in stalk integrity and yield (Roberto et al. 2009).

Certain mites can be employed in the biological control of other mite species. A well-known example is *Neoseiulus californicus*, a predatory mite commonly used to manage *Tetranychus urticae*, a highly polyphagous pest that affects a broad range of agricultural and horticultural crops, including cucumber, apple, and strawberry. *N. californicus* is widely integrated into biological control programs due to its effectiveness against phytophagous mites (McMurtry et al. 2015). *Neoseiulus californicus* preys on all developmental stages of *Tetranychus urticae* (i.e. eggs, larvae, nymphs, and adults), throughout its own life cycle. Notably, even in its larval stage, *N. californicus* is able to attack all life stages of its prey (Marafeli et al. 2011). In Brazil, *Neoseiulus californicus* is commercially available as a product called Spical-C (from Koppert).

The Sterile Insect Technique (SIT) has been used on fruit crops. SIT consists of mass-rearing target insect species, sterilizing males using gamma radiation or X-rays, and systematically releasing them into the environment to suppress wild pest populations through non-viable matings. When sterile males copulate with wild females, the resulting eggs fail to develop, leading to a progressive decline in pest populations over successive generations (Dyck et al. 2021). An example of the use of SIT technology in Brazil has been used by Moscamed, a biotechnology company from the state of Bahia. It has played a key role in controlling populations of the Mediterranean fruit fly (*Ceratitis capitata*) through release of sterile males, particularly the Vienna 8 tsl strain. Over time, this strategy reduces the pest population to levels that no longer cause economic damage to fruit crops (Silveira 2015).

Soil conditioning or restoration bioinputs

Bioinputs contribute to soil conditioning or restoration and can be divided into three categories: bioremediators, biorestorers, and biotransformers. Bioremediators use microorganisms, plants, or their enzymatic systems to neutralize or remove hazardous contaminants from polluted environments. It involves biodegradation—the enzymatic breakdown of pollutants into less toxic forms—and metabolic processes such as mineralization (complete conversion of organic compounds into inorganic products) and co-metabolism, where contaminants are degraded without serving as primary energy substrates for microbial metabolism (Gouma et al. 2014).

In the bioremediation category, the product Microbe-Lift IND is employed for the treatment of industrial and municipal effluents in lagoons, lakes, and soils. This formulation consists of a consortium of microorganisms, including *Rhodopseudomonas palustris*, *Pseudomonas stutzeri*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus amyloliquefaciens*, and *Pleomorphomonas oryzae*. This product is designed to facilitate the biodegradation of a wide range of organic and inorganic contaminants. It is particularly effective in the remediation of environments contaminated with organochlorine compounds and in the decontamination of organic sewage. The microbial consortium enhances the breakdown of complex organic matter, such as long-chain fatty acids, proteins, fats, greases, and starch. By accelerating the biological oxidation of these compounds, Microbe-Lift IND significantly improves the efficiency and stability of wastewater treatment processes in both aerobic and anaerobic systems (IBAMA 2022).

Another product within the same category is Micropan Petrol, a microbiological-enzymatic bioremediator designed for the degradation of hydrocarbons in soils and composting systems. This formulation contains *B. subtilis* and natural enzymes, which work synergistically to accelerate the breakdown of petroleum-derived contaminants. The combined action of *B. subtilis* and enzymatic components enhances the biodegradation process by catalyzing the decomposition of complex hydrocarbon molecules into simpler, less toxic compounds. This approach supports the effective remediation of hydrocarbon-polluted soils and organic waste environments, contributing to improved environmental quality and sustainable waste management practices (IBAMA 2018).

Biorestorers are biological compounds used in ecological restoration to rehabilitate degraded ecosystems, supporting the recovery of native species and ecological functions. They improve soil conditions, stimulate beneficial microbial activity, enhance nutrient cycling, and promote the reestablishment of native flora and fauna (Bullor et al. 2024).

Biotransformers are microorganisms used to accelerate the degradation of organic waste materials (Bullor et al. 2024).They can be utilized to break down organic wastes into bioproducts such as organic fertilizers and biogas (Hadidi et al. 2023). Biowaste can be biologically deconstructed into simpler compounds that are readily assimilated by plants, making them suitable for use as organic fertilizers. This process not only enhances soil fertility but also contributes to sustainable waste management. As a result, such biowaste-derived products can be effectively applied in agricultural settings, particularly for soil enrichment and restoration (Lakhal et al. 2020).

Opportunities and challenges for the expansion in bioinput use

Brazil is a world leader in the agribusiness sector, and has strategically prioritized sustainability by promoting innovation in agriculture. Recent events—such as the COVID-19 pandemic in 2020 and, more recently, the Russia-Ukraine war—have disrupted the global agrochemical supply chains and sparked growing interest among Brazilian farmers in alternative technologies.

In 2020, the National Bioinputs Program, established by MAPA via Decree No. 10.375, laid the groundwork for accelerating Brazil's biological-input sector by promoting research, innovation, and scaled production (MAPA 2020). This program has significantly contributed to the expansion of the bioinputs market in Brazil. As a consequence of this program, the demand for bioinputs in Brazil has increased over the years.

The development of bioinputs in Brazil holds substantial potential for promoting sustainable agriculture, particularly through the diversification of products for phytosanitary management. This innovation pathway represents a strategic opportunity to harness Brazil's extensive genetic and microbial diversity as a foundation for sustainable agricultural solutions. Although there has been a growing number of registered bioinputs and important initiatives—such as the National Bioinputs Program and Embrapa's Bioinsumos platform—several challenges persist. These include limited financial resources, and the need of more technical guidance to farmers (Oliveira et al. 2023). Additionally, further efforts are required to develop more products specifically adapted to tropical conditions, and to scale up production to meet the large-scale demands of Brazilian agriculture.

One important issue in Brazil that should be mentioned, is the practice of "on farm" bioinput production. This approach offers a cost-effective alternative that empowers farmers, reducing dependence on large agribusiness companies, and promoting decentralization of the agri-food supply chain. On-farm production of bioinputs is permitted provided that the production processes are conducted with strict rigor. However, small-scale farmers often lack the infrastructure necessary for proper fermentation and quality control, leading to a higher risk of contamination. Without rigorous monitoring of the production process for microorganism-based bioinputs, product quality may decline, and more importantly, harmful microorganisms could proliferate, posing potential health risks (Portal Embrapa 2021).

Additional areas that need to be addressed for microbial-based bioinputs are improvement in formulations through research to ensure stability under the harsh conditions commonly encountered on farms, including suboptimal storage and transport environments that may compromise microorganism viability. Moreover, as new products are developed, there is a need for their evaluation and dissemination of information to farmers on compatibility of bioinputs with conventional agricultural products, such as chemical pesticides, to enable their integrated use.

Conclusions

Bioinputs impact agriculture in several positive ways. In Brazil, bioinputs have become an important addition to the toolbox of sustainable agricultural practices available to farmers. The use of bioinputs may reduce the dependence on harmful chemical pesticides and synthetic fertilizers, thus being an important contribution to both responsible production and consumption sustainable development goals (SDG12). In a world where food security for ∼8 billion people is needed (SDG2), bioinputs will certainly be a key contribution to enhance crop yields in a sustainable manner. Furthermore, exclusive use of bioinputs or their use in combination with traditional synthetic fertilizers and pesticides can reduce water pollution (SDG 6) through runoff or leaching of chemicals from agricultural fields into water bodies or groundwater reservoirs. Nitrogen-fixing bacteria biofertilizers reduce the widespread use of synthetic nitrogen fertilizers, thus providing an indirect contribution to attain climate change action goals (SDG 13). This is because the production of synthetic nitrogen fertilizers is highly energy-intensive, relying on fossil fuels to generate energy and heat. As a result, this process releases CO_2, a greenhouse gas, exacerbating climate change. Furthermore, excessive amounts of synthetic nitrogen fertilizers in the soil increase naturally occurring microbial denitrification liberating N_2O, another greenhouse gas.

The ESG framework—which evaluates business and investment performance based on environmental, social, and governance criteria—can and should be applied to agriculture. This will support the transition to a more climate-resilient, socially equitable, and ethically governed food system. In this context, bioinputs are already contributing significantly to shape a new and more sustainable model of agriculture.

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Data availability

There are no new data associated with this article.

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