Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Overview of Bioinput Commercialization for Staple Food Crops in Central-Southern Brazil (2019–2023)

Marcia Orth Ripke
Universidade Comunitária da Região de Chapecó (Unochapecó)
Vanessa da Silva Corralo
Universidade Comunitária da Região de Chapecó (Unochapecó)
Carolina Riviera Duarte Maluche Baretta
Universidade Comunitária da Região de Chapecó (Unochapecó)
Flávio Roberto Mello Garcia
Universidade Federal de Pelotas
Junir Antônio Lutinski
junir@unochapeco.edu.br
Universidade Comunitária da Região de Chapecó (Unochapecó)

Research Article

Keywords: Biological control, Biofertilizers, Microbial inputs, Natural products, Food safety

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10989085/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

The transition toward the use of bioinputs represents a strategic pillar for the sustainability and resilience of global food systems; however, patterns of their practical adoption in staple food crops across the Global South remain poorly quantified. This study investigated the commercialization of bioinputs in Central-Southern Brazil from 2019 to 2023 for crops included in the Brazilian Basic Food Basket, using official data from agricultural defense agencies in the states of Mato Grosso, Paraná, Rio Grande do Sul, and Santa Catarina. Active ingredients and commercialized volumes were quantified for rice, coffee, sugarcane, common bean, soybean, and wheat. The relative volume of biological products compared with synthetic products was highest for wheat (0.29%), followed by soybean (0.06%). Regarding bioinput diversity, soybean accounted for the highest relative proportion (7.29%), followed by rice (6.15%). A total of 32 individual biological active ingredients were identified, with soybean showing the greatest diversity (n = 30). Microbial agents dominated the market (78.12%; n = 25), comprising fungi (34.37%; n = 11), bacteria (28.12%; n = 9), and viruses (15.62%; n = 5), with viral agents restricted to baculoviruses used in soybean. Botanical products accounted for 21.87% (n = 7). The bioinsecticide *Bacillus thuringiensis* showed the broadest commercialization across all evaluated crops, followed by a common pattern of commercialization of *Bacillus subtilis*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Purpureocillium lilacinum*, and *Trichoderma harzianum* across sugarcane, common bean, soybean, and wheat. Among botanical products, *Azadirachta indica* and *Sophora flavescens* were prominent in rice, coffee, common bean, and soybean. The findings demonstrate the heterogeneous expansion of bioinputs across the region and provide an empirical basis for public policies and scientific strategies aimed at strengthening food security and ecosystem integrity. Future studies should maintain longitudinal monitoring of bioinput commercialization to inform regional guidelines and support the consolidation of sustainable agricultural systems.

Introduction

Bioinputs comprise products, processes, or technologies derived from plant, animal, or microbial sources that are designed to promote plant growth, enhance nutrient uptake, and mitigate biotic and abiotic stresses in agricultural systems [1, 2]. Ranging from macroorganisms, such as predatory insects and mites, to microorganisms (bacteria, fungi, and viruses) and botanical extracts, these biotechnologies can be applied throughout agricultural, aquaculture, and forestry production chains, including processing and postharvest stages [1, 3].

Characterized by high target specificity, low mammalian toxicity, and rapid environmental degradation, bioinputs can substantially reduce the risks of bioaccumulation and water contamination [4, 5]. These characteristics make them important tools for maintaining agroecosystem balance and supporting the transition toward sustainable agriculture. Their adoption in agricultural production has been driven by their demonstrated biological effectiveness and their synergistic integration with Integrated Pest Management (IPM), synthetic chemical control, and plant nutrition strategies [6–8].

To provide a regulatory framework for this transition, Brazilian Law No. 15,070/2024 established the national legal framework for bioinputs, standardizing the registration and use of biostimulants, semiochemicals, biological control agents, biofertilizers, and inoculants in conventional, organic, and agroecological production systems [3]. Although Brazilian agriculture remains highly dependent on synthetic inputs, with pesticide sales reaching approximately 825.8 thousand metric tons compared with 89.8 thousand metric tons of biological products in 2024 [9], recent regulatory advances are intended to address this historical imbalance.

The technical feasibility of biological technologies is well established in major crops and agricultural commodities. In soybean [*Glycine max* (L.) Merr.], inoculation with *Bradyrhizobium* spp. represents a globally recognized benchmark for biological nitrogen fixation, supplying the crop's nitrogen requirements without the need for synthetic nitrogen fertilizers [10, 11]. In sugarcane (*Saccharum officinarum* L.), entomopathogenic agents such as *Metarhizium anisopliae* (Metschn.) Sorokīn (1883) and *Beauveria bassiana* (Bals.-Criv.) Vuill. (1912) are widely used to control the sugarcane spittlebug [*Mahanarva fimbriolata* (Stål, 1854)] and sugarcane borer [*Diatraea saccharalis* (Fabricius, 1794)], respectively [12]. Similarly, in wheat (*Triticum aestivum* L.), bionematicides and biofungicides formulated with *Bacillus subtilis* (Ehrenberg 1835) Cohn 1872 and *Trichoderma harzianum* Rifai (1969) are effective in managing root disease complexes and root-knot nematodes (*Meloidogyne* spp.) [13–15].

This agronomic effectiveness supports strong market growth projections. Globally, the bioinputs sector is projected to expand at a compound annual growth rate (CAGR) of approximately 13% through 2032 [15]. In Brazil, the market is expected to grow by approximately 23% annually through 2030, driven by the rapid expansion of bioinput use, which reached approximately 84 million hectares during the 2023/2024 growing season [16]. Soybean accounted for 55% of this treated area, followed by corn (27%), sugarcane (12%), and high-value crops, including cotton, coffee, citrus, fruits, and vegetables (6%) [17]. Nematode management is the leading commercial segment, accounting for more than 40% of the total volume of biological products marketed [15].

Moreover, the expansion of these biotechnologies has been accelerated by increasing pest resistance to synthetic active ingredients and the need to optimize production costs. At the same time, the adoption of biological inputs can contribute to restoring soil microbial communities, improving soil water retention, and enhancing organic carbon sequestration, thereby aligning agricultural production with global climate goals [8, 18–21]. From a macroeconomic perspective, strengthening domestic bioindustrial capacity is also strategically important for increasing the resilience and sovereignty of agricultural supply chains by reducing dependence on imported synthetic chemical precursors [22].

Alongside these agronomic drivers, increasing consumer demand for safe foods with reduced toxic residues has positioned bioinputs as an important component of food quality. This is particularly relevant to crops included in the Brazilian Basic Food Basket, whose products are primarily intended for consumption in natura or after minimal processing [23, 24]. Consequently, the transition toward biologically based inputs extends beyond agricultural sustainability and may also contribute to public

health by reducing risks associated with continuous dietary exposure to toxic contaminants and supporting the Human Right to Adequate and Healthy Food [4, 25–27].

Despite these projections, empirical evidence quantifying the commercialization of bioinputs in crops that are strategically important for food security in the Global South remains scarce. To address this knowledge gap, this study investigated the commercialization dynamics of bioinputs for major crops included in the Brazilian Basic Food Basket in Central-Southern Brazil between 2019 and 2023. The analysis focused on six essential crops: rice (*Oryza sativa* L.), coffee (*Coffea* spp.), sugarcane (*S. officinarum*), common bean (*Phaseolus vulgaris* L.), soybean (*G. max*), and wheat (*T. aestivum*), which together account for approximately 46% of the items included in the Brazilian Basic Food Basket. The study area encompassed major agricultural production regions across four Brazilian states: Mato Grosso, Paraná, Rio Grande do Sul, and Santa Catarina.

Material and Methods

Study design and geographical scope

This study used a descriptive, quantitative design based on the documentary analysis of secondary data to investigate the commercialization patterns of agricultural bioinputs. The study area encompassed four strategically important states in Central-Southern Brazil: Mato Grosso, Paraná, Rio Grande do Sul, and Santa Catarina. These states were selected because of their substantial contribution to Brazilian agricultural production, supplying both the domestic market and export markets.

Together, these four states accounted for approximately 57% of Brazil's total production of cereals, legumes, and oilseeds in 2025, representing more than 197 million metric tons of grain [28]. Mato Grosso accounted for the largest share (32.0%), followed by Paraná (13.5%), Rio Grande do Sul (9.3%), and Santa Catarina (approximately 2.2%). These states are also major producers of crops included in the Brazilian Basic Food Basket and therefore play a central role in food and nutrition security in Brazil.

Six major crops were included in the analysis: rice (*Oryza sativa* L.), coffee (*Coffea* spp.), sugarcane (*Saccharum officinarum* L.), common bean (*Phaseolus vulgaris* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.).

Official data acquisition

Bioinput commercialization data for the crops included in the study, covering the period from 2019 to 2023, were obtained from official state agricultural defense agencies through two different approaches. For Mato Grosso, raw records were retrieved directly from the public database maintained by the Instituto de Defesa Agropecuária do Estado de Mato Grosso (INDEA). For Paraná, Rio Grande do Sul, and Santa Catarina, access to the databases was requested through the Brazilian federal government transparency platform (Gov.br), pursuant to the Brazilian Access to Information Law (Law No. 12,527/2011). Requests were submitted to the Agência de Defesa Agropecuária do Paraná (ADAPAR), Secretaria da Agricultura do

Rio Grande do Sul (SEAPI), and Companhia Integrada de Desenvolvimento Agrícola de Santa Catarina (CIDASC), respectively.

A temporal limitation was identified for Santa Catarina, where detailed crop-specific commercialization data were available only for 2022 and 2023.

Data curation and categorization of active ingredients

The initial database comprised all active ingredients (AIs) commercialized for each crop between 2019 and 2023, including both synthetic chemical compounds and biological agents. From this comprehensive dataset, a specific database was created to identify and isolate biological active ingredients. The selection included exclusively microbial agents (bacteria, fungi, and viruses) and botanical compounds (plant extracts and essential oils), whereas synthetic chemical pesticides were systematically excluded.

The compiled bioinput database was categorized according to active ingredient diversity, commercialized volumes, toxicological classification, environmental hazard potential, agronomic function, major biological targets, and mode of action. Data were verified and cross-referenced against official sources, including the Sistema de Agrotóxicos Fitossanitários (AGROFIT) [29], the Bioinsumos application of the Brazilian Ministry of Agriculture and Livestock (MAPA) [30], and authorized monographs from the Brazilian Health Regulatory Agency (Anvisa) [31, 32].

The toxicological hazard classification and environmental hazard potential of the biological products followed the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) [5] and the guidelines of the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) [33], respectively.

Data processing and statistical analysis

Based on the total set of commercialized active ingredients, the relative percentages of bioinputs and their respective market shares by volume were calculated in relation to the total volume of active ingredients commercialized. Data were summarized using descriptive statistics and frequency analysis, and the results were presented in tables and analytical graphs.

Results

During the study period, the commercialization profile across the evaluated states was dominated by synthetic chemical products, which accounted for an average of 94.3% of the total commercialized products, whereas bioinputs represented 5.7%. The relative volume of biological active ingredients compared with synthetic active ingredients varied substantially among crops, with the highest proportion recorded for wheat (0.29%), followed by soybean (0.06%). The lowest relative proportions were observed for rice (0.02%), coffee (0.02%), and common bean (0.01%) (Fig. 1). The geographical distribution of bioinput commercialization also varied among states. Paraná had the highest commercialized volumes

for coffee, common bean, soybean, and wheat, whereas Rio Grande do Sul and Mato Grosso accounted for the largest shares of sales for rice and sugarcane, respectively.

Regarding the diversity of biological active ingredients commercialized in the states analyzed, soybean showed the highest relative proportion (7.29%), followed by rice (6.15%), common bean (5.60%), and wheat (5.59%). The lowest proportions were recorded for sugarcane (4.63%) and coffee (2.24%) (Fig. 2).

A total of 32 distinct biological active ingredients were identified as having been commercialized during the study period. Soybean showed the greatest diversity of commercialized biological active ingredients (n = 30), followed by wheat (n = 18) and common bean (n = 17). Lower numbers were recorded for sugarcane (n = 9), rice (n = 3), and coffee (n = 3) (Table 1).

Microbial control agents (fungi, bacteria, and viruses) predominated among the bioinputs identified, accounting for 78.12% (n = 25) of all active ingredients evaluated. Fungi were the most represented group, accounting for 34.37% (n = 11), followed by bacteria at 28.12% (n = 9) and viral bioagents (baculoviruses) at 15.62% (n = 5). Botanical active ingredients, including plant extracts and essential oils, accounted for 21.87% (n = 7) of the total (Table 1).

Considering all six crops analyzed, the microbial insecticide *Bacillus thuringiensis* Berliner 1915 showed the broadest commercialization pattern and was recorded for all evaluated crops. A common commercialization pattern of biological control agents was observed across sugarcane, common bean, soybean, and wheat, particularly for the bacterium *B. subtilis* and the entomopathogenic and nematophagous fungi *B. bassiana*, *M. anisopliae*, *Purpureocillium lilacinum* (Thom) Luangsa-ard, Houbraken, Hywel-Jones & Samson (2011), and *T. harzianum*. Among plant-derived active ingredients, *Azadirachta indica* A. Juss. and *Sophora flavescens* Aiton were commercialized for four crops: rice, coffee, common bean, and soybean (Table 1).

From a socioenvironmental regulatory perspective, all bioinputs analyzed (n = 32; 100%) were classified as Environmental Hazard Class IV (Slightly Hazardous to the Environment). Likewise, regarding human toxicity, 100% of the active ingredients met the criteria for GHS Category 5 (Unlikely to Cause Acute Harm) or were classified as Not Classified (Table 1).

Table 1
Bioinputs commercialized for rice (*Oryza sativa* L.), coffee (*Coffea* spp.), sugarcane (*Saccharum officinarum* L.), common bean (*Phaseolus vulgaris* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) in Central-Southern Brazil (2019–2023)

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Beauveria bassiana (Bals.-Criv.) Vuill. (1912) Entomopathogenic fungus	Microbiological insecticide	It acts through contact via conidial germination, enzymatic and mechanical penetration of the tegument, systemic colonization, and lysis of host tissue.	*Bemisia tabaci* (Gennadius, 1889) (whitefly); *Dalbulus maidis* (DeLong, 1923) (corn leafhopper); *D. saccharalis* (sugarcane borer); *Hypothenemus hampei* (Ferrari, 1867) (coffee borer); *Tetranychus urticae* Koch, 1836 (spider mite)	sugarcane, beans, soybeans, wheat
Cordyceps fumosorosea (Wize) Kepler, B. Shrestha & Spatafora (2017) Entomopathogenic fungus	Microbiological insecticide	It acts through contact via conidial germination, enzymatic-mechanical penetration of the tegument, systemic colonization, and tissue lysis.	*B. tabaci* (whitefly); *D. maidis* (corn leafhopper); *D. saccharalis* (sugarcane borer); *H. hampei* (coffee borer); T. *urticae* (striped mite)	beans, soybeans, wheat
Cordyceps javanica (Frieder. & Bally) Kepler, B. Shrestha & Spatafora (2017) Entomopathogenic fungus	Microbiological insecticide	It acts through contact via conidial germination, enzymatic penetration of the cuticle, systemic colonization, septicemia, and nutritional depletion of the host.	*D. maidis* (corn leafhopper); *Euschistus heros* (Fabricius, 1798) (brown stink bug); *Frankliniella schultzei* (Trybom, 1910) (thrips); *Sphenophorus levis* Vaurie, 1978 (sugarcane weevil)	beans, soybeans, wheat

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Metarhizium anisopliae (Metschn.) Sorokīn 1883 Entomopathogenic fungus	Microbiological insecticide	It acts through enzymatic-mechanical penetration of the cuticle, systemic colonization, and death due to septicemia, mycosis, and nutritional depletion.	*D. maidis* (corn leafhopper); *Deois flavopicta* (Stål, 1854) / *Zulia entreriana* (Berg, 1879) (pasture leafhoppers); *M. fimbriolata* (root leafhopper); *Sphenophorus levis* Vaurie, 1978 (sugarcane leafhopper)	sugarcane, beans, soybeans, wheat
Pochonia chlamydosporia (Goddard) Zare & W. Gams 2001 Nematophagous fungus	Microbiological nematicide	It acts through oviparasitism and parasitism of females in the rhizosphere via enzymatic-mechanical appressorial penetration, causing embryonic degradation and reproductive suppression.	*Heterodera glycines* Ichinohe, 1952 (cyst nematode); *Meloidogyne incognita* (Kofoid & White, 1919) Chitwood, 1949 (root-knot nematode); *Meloidogyne javanica* (Treub, 1885) Chitwood, 1949 (root-knot nematode); *Pratylenchus brachyurus* (Godfrey, 1929) Filipjev & Schuurmans Stekhoven, 1941 (lesion nematode)	soybeans, wheat
Purpureocillium lilacinum (Thom) Luangsa-ard, Houbraken, Hywel-Jones & Samson (2011) Nematophagous fungus	Microbiological nematicide	It acts through contact via the parasitism of eggs, females, and juveniles, involving enzymatic-mechanical penetration of the cuticle, tissue lysis, and the inactivation of the nematodes.	*H. glycines* (cyst nematode); *M. incognita* (gall nematode); *M. javanica* (gall nematode); *P. brachyurus* (lesion nematode)	sugarcane, beans, soybeans, wheat

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Saccharomyces cerevisiae Meyen ex E.C. Hansen (1883) Elicitor fungus/yeast	Microbiological fungicide/plant defense elicitor. Markers: β-glucans, mannans, and chitin	It acts as a elicitor by activating the innate immune response (PTI) through the recognition of PAMPs by PRRs, thereby inducing the synthesis of phytoalexins, PR proteins, and tissue lignification.	*Alternaria* spp. (Alternaria leaf spot); *Botrytis cinerea* Pers. (1794) (gray mold); *Colletotrichum* spp. (anthracnose); *Penicillium* spp. (green mold/blue mold)	soybeans
Trichoderma afroharzianum P. Chaverri, F.B. Rocha, Degenkolb & Druzhin. (2015) Mycoparasitic fungus	Microbiological fungicide and nematicide	Multifunctional agent: acts through enzymatic mycoparasitism, antibiosis, niche competition, and induction of systemic resistance (ISR) following root colonization.	*Fusarium oxysporum* Schlecht. 1824 (Fusarium wilt / root rot); *P. brachyurus* (root lesion nematode); *Rhizoctonia solani* J.G. Kühn 1858 (damping-off / root rot); *Sclerotinia sclerotiorum* (Lib.) de Bary 1884 (white mold)	soybeans, wheat
Trichoderma asperellum Samuels, Lieckf. & Nirenberg (1999) Mycoparasitic fungus	Microbiological fungicide and nematicide	Sclerodium mycoparasite: acts through cell lysis, niche competition, and induction of systemic resistance (ISR) in the plant.	*F. oxysporum* (Fusarium wilt/root rot); *P. brachyurus* (lesion nematode); *R. solani* (root rot/damping-off); *S. sclerotiorum* (white mold)	beans, soybeans, wheat
Trichoderma harzianum Rifai (1969) Mycoparasitic fungus	Microbiological fungicide and nematicide	It acts through mycoparasitism, antibiosis, and niche competition, promoting root development and the induction of systemic resistance (ISR).	*F. oxysporum* (Fusarium wilt/root rot); *M. incognita* (gall nematode); *R. solani* (root rot/damping-off); *S. sclerotiorum* (white mold)	sugarcane, beans, soybeans, wheat

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Trichoderma koningiopsis Samuels, C. Suárez & H.C. Evans (2006) Mycoparasitic fungus	Microbiological fungicide and nematicide	It acts through lytic mycoparasitism, antibiosis, and niche competition, promoting root biostimulation and inducing systemic resistance (ISR).	*F. oxysporum* (Fusarium wilt/root rot); *Pythium* spp. (damping-off/seedling rot); *R. solani* (root rot/damping-off); *S. sclerotiorum* (white mold)	soybeans, wheat
Bacillus firmus Bredemann 1908 Gram-positive bacterium	Microbiological nematicide. (via seed treatment and post-emergence/planting furrow application)	Root biofilm formation, competition for nutrients, secretion of nematicidal metabolites, and egg parasitism.	*M. incognita* (gall nematode); *M. javanica* (gall nematode); *P. brachyurus* (lesion nematode)	soybeans
Bacillus licheniformis (Weigmann 1898) Chester 1901 Gram-positive bacterium	Microbiological nematicide. (via seed treatment, seedbed application, and post-emergence soil drenching)	Competition for space and nutrients in the rhizosphere and for the production of metabolites and enzymes (chitinases and proteases).	*H. glycines* (soybean cyst nematode); *M. incognita* (gall nematode); *Meloidogyne exigua* Göldi, 1887 (coffee gall nematode); *P. brachyurus* (root lesion nematode)	soybeans, wheat
Bacillus paralicheniformis Dunlap *et al*. 2015 Gram-positive bacterium	Microbiological nematicide and insecticide, applied via seed treatment (ST) and in-furrow	Formation of a protective biofilm on the roots and release of secondary metabolites, leading to the mortality of juvenile nematodes and a reduction in the viability of nematode eggs.	*H. glycines* (soybean cyst nematode); *M. incognita* (gall nematode); *P. brachyurus* (root lesion nematode); *Rotylenchulus reniformis* Linford & Oliveira, 1940 (kidney-shaped nematode)	soybeans
Bacillus pumilus Meyer & Gottheil 1901 Gram-positive bacterium	Microbiological fungicide	Direct antagonism through the release of antifungal compounds (which inhibit spores and mycelium) and the induction of systemic	*Alternaria porri* (Ellis) Cif. (1930) (purple spot); *Botrytis cinerea* Pers. (1794) (gray mold); *Cryptosporiopsis perennans* Zeller	beans, soybeans, wheat

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
		resistance in the plant.	& Childs (1925) (bull's-eye rot); *Phakopsora pachyrhizi* Syd. & P. Syd. (1914) (Asian soybean rust); *Sphaerotheca macularis* (Wallr.) Lind (1913) (powdery mildew)	
Bacillus subtilis (Cohn 1872) Prazmowski 1880 Gram-positive bacterium	Microbiological fungicide, bactericide, and nematicide	Biocontrol through antibiosis and competition, combined with the induction of systemic resistance and the promotion of plant growth.	*A. por*ri (purple spot); *Hemileia vastatrix* Berk. & Broome (1869) (coffee rust); *M. incognita* (gall nematode); *Pratylenchus zeae* Graham, 1951 (root lesion nematode)	sugarcane, beans, soybeans, wheat
Bacillus thuringiensis Berliner 1915 *(subsp. kurstaki, subsp. aizawai, subsp. israelensis)* Gram-positive bacterium	Microbiological insecticide	Ingestion of δ-endotoxins (Cry and Vip), which, once solubilized in the insect's alkaline midgut, cause cell lysis and epithelial porosity due to osmotic shock.	*Chrysodeixis includens* (Walker, 1858) (false measuring caterpillar); *Helicoverpa armigera* (Hübner, 1808) (*Helicoverpa caterpillar*); *Plutella xylostella* (Linnaeus, 1758) (cabbage moth); *Spodoptera frugiperda* (J.E. Smith, 1797) (fall armyworm)	rice, coffee, sugarcane, beans, soybeans, wheat

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Bacillus velezensis Ruiz-García *et al*. 2005 Gram-positive bacterium	Microbiological fungicide and nematicide	Formation of a protective biofilm in the rhizosphere (physical barrier), release of lipopeptides and lytic enzymes, and induction of systemic resistance in the plant.	*F. oxysporum* (Fusarium wilt); *H. glycines* (soybean cyst nematode); *M. incognita* (gall nematode); *P. brachyurus* (root lesion nematode)	beans, soybeans, wheat
Pseudomonas chlororaphis (Guignard & Sauvageau 1894) Bergey *et al*. 1930 Gram-negative bacteria / plant growth promoters (PGPs).	Microbiological fungicide and nematicide	It acts through antibiosis via secondary metabolites (such as phenazines), rhizosphere competition, and induction of systemic resistance (ISR) against plant pathogens and nematodes.	*M. incognita* (gall nematode); *M. javanica* (gall nematode); *P. brachyurus* (lesion nematode); *R. solani* (damping-off/root rot)	sugarcane, soybeans, wheat
Pseudomonas fluorescens Flügge 1886 Gram-negative bacteria / PGP	Microbiological fungicide and nematicide	It acts through iron chelation (via siderophores), antibiosis, rhizosphere competition, and induction of systemic resistance (ISR) against plant pathogens and nematodes.	*Fusarium* spp. (root rot/Fusarium wilt); *M. incognita* (gall nematode); *P. brachyurus* (lesion nematode); *R. solani* (damping-off/root rot)	soybeans, wheat
Allium sativum L. Garlic (Bulbs) Plant extract	Phytochemical nematicide. Markers: Diallyl disulfide and diallyl trisulfide	Contact and biofumigation (paralysis of juveniles, inhibition of egg hatching, and nematode mortality).	*H. glycines* (soybean cyst nematode); *M. incognita* (gall nematode); *P. brachyurus* (lesion nematode	sugarcane, beans, soybeans
Azadirachta indica A. Juss. (neem oil) Pure vegetable oil from the seeds	Phytochemical insecticide and acaricide. Markers and active ingredients: limonoids, azadirachtin A, and azadirachtin B	Antifeedant, repellent, growth regulator (interferes with ecdysone/molting), ovicidal and larvicidal action.	*B. tabaci* (whitefly); *Liriomyza* spp. (leafminer); *S. frugiperda* (cutworm); *T. urticae* (striped mite)	rice, coffee, beans, soybeans

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Cinnamomum verum J. Presl Cinnamon essential oil	Botanical insecticide. Phytochemical marker: (E)-cinnamaldehyde (trans-cinnamaldehyde)	It acts through contact and ingestion via cinnamaldehyde, disruption of cell membranes, neurotoxicity, and a dislodging-repellent effect on insects.	*B. tabaci* biotype B (whitefly); *T. urticae* (striped mite); *Aphis gossypii* Glover, 1877 (cotton aphid / inflorescence aphid); *F. occidentalis* (thrips)	soybeans
Citrus sinensis (L.) Osbeck Essential oil from orange peel	Botanical insecticide, acaricide, and fungicide. Phytochemical marker: D-limonene	It works by dissolving the cuticular cement and cell walls, promoting rapid desiccation and the release of fluids.	*B. tabaci* biotype B (whitefly); *F. occidentalis* (thrips); *Pseudococcus viburni* (Signoret, 1875) (mealybug); T. *urticae* (spotted mite)	beans, soybeans, wheat
Melaleuca alternifolia (Maiden & Betche) Cheel Essential oil	Plant fungicide and bactericide. Phytochemical marker: Terpinen-4-ol	It acts through contact and vapor phase, promoting the lysis of the cell membrane of plant pathogens and the degradation of the cuticular wax of arthropods, resulting in cellular leakage and desiccation.	*Cercospora beticola* Sacc. (1876) (cercosporiosis); *Colletotrichum gloeosporioides* (Penz.) Penz. & Sacc. (1884) (anthracnose); *Sclerotinia sclerotiorum* (Lib.) de Bary (1884) (white mold); *Xanthomonas campestris* (Pammel 1895) Dowson 1939 (bacterial crown rot / bacterial spot)	sugarcane, beans
Reynoutria sachalinensis (F. Schmidt) Nakai Plant extract	Biochemical fungicide/Plant defense inducer. Markers: Emodin, emodin-1-O-β-D-glycoside, resveratrol, resveratrol-3-O-β-D-glycoside, and fiscion	It activates the plant's natural defense mechanisms through Systemic Acquired Resistance (SAR/ISR), stimulating the production of phytoalexins and	*Colletotrichum lindemuthianum* (Sacc. & Magnus) Briosi & Cavara (1889) (anthracnose); *Erysiphe polygoni* DC. (1805) (powdery mildew); *Phaeoisariopsis*	beans

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
		cell thickening to prevent fungal infection.	*griseola* (Sacc.) Ferraris (1909) (angular leaf spot); *S. sclerotiorum* (white mold)	
Sophora flavescens Aiton Plant extract	Botanical insecticide and acaricide. Active ingredients: Oxymatrine/Matrine	It acts through contact and ingestion by modulating acetylcholine receptors and inhibiting chitinase during ecdysis, thereby inducing paralysis and mortality.	*Anticarsia gemmatalis* Hübner, 1818 (soybean looper); *B. tabaci* (Gennadius, 1889) biotype B / MEAM1 (whitefly); *Leucoptera coffeella* (Guérin-Méneville, 1842) (coffee leaf miner)	rice, coffee, beans, soybeans
Anticarsia gemmatalis multiple nucleopolyhedrovirus - AgMNPV *Alphabaculovirus aggemmatalis* Virus / Baculoviridae	Microbial insecticide. Foliar application on soybean crops	It acts upon ingestion, releasing virions in the alkaline midgut that infect tissues systemically, causing cell lysis and the collapse of the insect.	*A. gemmatalis* (soybean caterpillar)	soybeans
Chrysodeixis includens nucleopolyhedrovirus (ChinNPV) *Alphabaculovirus chincludentis* Virus / Baculoviridae	Microbiological insecticide	It acts upon ingestion, releasing virions in the intestine. Viral replication causes tissue lysis and liquefaction of the insect, facilitating its spread throughout the crop.	*Chrysodeixis includens* (Walker, 1858) (false measuring caterpillar)	soybeans
Helicoverpa armigera nucleopolyhedrovirus – HearNPV *Alphabaculovirus hearmi* Virus /Baculoviridae	Microbiological insecticide	It acts upon ingestion, releasing virions in the intestine. Viral replication causes tissue lysis and liquefaction of the insect, as well as secondary contamination of the crop.	*Helicoverpa armigera* (Hübner, 1808) (Old World armyworm)	soybeans

Biological agent	Agronomic classification	Mechanism of action	Major targets for Biological Control	Crops evaluated
Helicoverpa zea single nucleopolyhedrovirus (HzSNPV) *Alphabaculovirus hezea* Virus / Baculoviridae	Microbiological insecticide	It acts upon ingestion, releasing virions in the intestine. Viral replication causes tissue lysis and liquefaction of the insect, as well as secondary contamination of the crop.	*H. armigera* (Old World armyworm); *Helicoverpa zea* (Boddie, 1850) (corn earworm)	soybeans
Spodoptera frugiperda multiple nucleopolyhedrovirus (SfNPV) *Alphabaculovirus spofrugiperdae* Virus/ Baculoviridae	Microbiological insecticide	It acts upon ingestion, releasing virions in the intestine. Viral replication causes tissue lysis and liquefaction of the insect, as well as secondary contamination of the crop.	*S. frugiperda* (corn earworm).	soybeans

Note

Data compiled by the authors from official pesticide and bioinput commercialization records provided by INDEA (Mato Grosso), ADAPAR (Paraná), SEAPI (Rio Grande do Sul), and CIDASC (Santa Catarina) (2019–2023).

Discussion

This study mapped the commercialization of bioinputs between 2019 and 2023 in the states of Mato Grosso (MT), Paraná (PR), Rio Grande do Sul (RS), and Santa Catarina (SC), encompassing major crops included in the Brazilian Basic Food Basket (rice, coffee, sugarcane, common bean, soybean, and wheat). Bioinput commercialization followed regional agricultural production patterns, with Paraná leading sales for coffee, common bean, soybean, and wheat, whereas Rio Grande do Sul and Mato Grosso accounted for the largest commercialized volumes for rice and sugarcane, respectively. This pattern is consistent with consolidated data from IBAMA [9], which showed that Paraná remained the leading Brazilian market for biological products in 2024, with approximately 21,000 metric tons commercialized, followed by Mato Grosso with approximately 16,800 metric tons and Rio Grande do Sul with approximately 12,500 metric tons. In contrast, substantial regional disparities placed Santa Catarina 15th nationally, with 437 metric tons commercialized.

According to our findings, the relative contribution of biological products compared with the total volume of synthetic products was highest for wheat, followed by soybean. Conversely, soybean showed the

greatest diversity of commercialized bioinputs. The prominence of Paraná and Rio Grande do Sul in national wheat production [28] reinforces the role of Southern Brazil as the country's major center for the consumption and adoption of biological control technologies in this crop. This regional pattern contrasts with the broader Brazilian market, in which soybean accounts for more than half of the total revenue generated by biological products, driven predominantly by the use of inoculants, bionematicides, and bioinsecticides [17, 34]. At the national level, soybean therefore remains the primary destination for both biological and synthetic products, reflecting its extensive cultivated area and the substantial phytosanitary pressure associated with its production system [4, 9].

Regarding the characteristics of the commercialized bioinputs, microbial agents (fungi, bacteria, and viruses) predominated, followed by products of botanical origin. Microbial biopesticides act through mechanisms including antagonism, predation, parasitism, antibiosis, and the production of inhibitory toxins [35]. Botanical compounds, in turn, exert multifunctional control by disrupting the life cycles of target organisms, acting through behavioral and physiological inhibition in insects and through structural degradation of cell membranes and cell walls in phytopathogenic fungi [36, 37].

The commercial predominance of microbial products is consistent with the international pattern reported by Jalloh et al. [16], according to which microorganisms account for approximately 65% of biocontrol products registered worldwide, with the remaining share represented by macroorganisms and botanical extracts. At the national level, this distribution reflects the composition of products officially registered in the Bioinsumos platform maintained by the Brazilian Ministry of Agriculture and Livestock [30], where microbial agents with acaricidal, bactericidal, fungicidal, insecticidal, and nematicidal activity constitute the leading biocontrol segment, followed by biochemical and semiochemical products and macroorganisms. This pattern reinforces Brazil's prominent role in the adoption of agricultural biotechnologies: during the 2023/2024 growing season, the area treated with bioinputs exceeded 84 million hectares, corresponding to 36% of the country's total agricultural area and consolidating these products as important components of contemporary crop protection [34].

In sugarcane, common bean, soybean, and wheat, the fungi *B. bassiana*, *M. anisopliae*, *P. lilacinum*, and *T. harzianum* were among the most widely commercialized biological agents. In Brazil, the genus *Trichoderma* stands out as one of the major biological control agents because of its high adaptive plasticity under local soil and climatic conditions and its effectiveness in managing different pathosystems [38]. Among the species of greatest commercial and ecological relevance in the country are *Trichoderma asperellum*, *Trichoderma harzianum*, *Trichoderma viride*, *Purpureocillium chlamydosporium*, and *Purpureocillium lilacinum* [30]. These microorganisms have multifunctional roles in suppressing soilborne phytopathogens and nematodes, promoting plant growth, and inducing systemic resistance in host plants. Their success as biological control agents stems from their ability to survive saprophytically in soil and from the specificity of their mechanisms of action, including rapid rhizosphere competition by *Trichoderma* spp. and the enzymatic and toxin-mediated degradation of nematode eggs by *Purpureocillium* spp. [39, 40].

Among bacteria, the genus *Bacillus* stood out because of its high frequency of commercialization, particularly *B. subtilis* in sugarcane, common bean, soybean, and wheat. *Bacillus thuringiensis* (Bt), in turn, was recorded for all evaluated crops and was the most commercially prominent entomopathogenic species. This pattern is consistent with the long-standing global importance of this genus in agricultural biological control [14, 41]. The high effectiveness of *B. thuringiensis* results from the production of parasporal protein crystals (Cry and Cyt proteins) during sporulation, which cause osmotic lysis of the intestinal epithelium of susceptible insects [42]. Notably, native protoxins contained in commercial formulations remain effective even against lepidopteran populations resistant to transgenic Bt events, supporting the strategic role of these bioinsecticides in insecticide-resistance management [43]. In Brazil, officially registered products are predominantly based on *B. thuringiensis* subsp. *kurstaki* and *B. thuringiensis* subsp. *aizawai* [29] and are intended to control key pests such as *H. armigera*, *A. gemmatalis*, *S. frugiperda*, *Tuta absoluta* (Meyrick, 1917), and *P. xylostella*.

The biotechnological potential of the genus *Bacillus* extends beyond biological control to multifunctional plant protection and growth promotion through both direct and indirect mechanisms [44]. Species such as *B. subtilis* and *B. amyloliquefaciens* are particularly relevant because of their ability to synthesize phytohormones and secondary metabolites with broad-spectrum antimicrobial activity, in addition to the documented antiviral and nematicidal activity of *B. amyloliquefaciens* [40, 44, 45]. Similarly, *B. pumilus* modulates host physiology through the release of gibberellins [46, 47], whereas *B. licheniformis* exerts direct antagonistic activity mediated by serine proteases [48, 49]. This combination of physiological effects and diverse modes of action establishes the genus *Bacillus* as a major platform for the development of highly effective agricultural bioinputs.

Completing the spectrum of microbial crop-protection products, members of the family Baculoviridae, although commercialized less frequently in the present study, were particularly relevant to soybean because of their high host specificity in the biological control of lepidopteran pests. The major viral biopesticides identified included *Anticarsia gemmatalis* nucleopolyhedrovirus (AgMNPV), *Helicoverpa armigera* nucleopolyhedrovirus (HearNPV), and *Spodoptera frugiperda* nucleopolyhedrovirus (SfNPV). Following ingestion of treated foliage, the proteinaceous occlusion bodies of these agents dissolve under the alkaline conditions of the host midgut, releasing virions that infect epithelial cells [50]. Subsequent tissue liquefaction facilitates pathogen dissemination within the crop environment, promoting further infection of susceptible pest populations.

Among botanical insecticides, *A. indica* A. Juss. and *S. flavescens* Aiton showed similar commercialization patterns across rice, coffee, common bean, and soybean. Oil extracted from *A. indica*, whose principal active component is the tetranortriterpenoid azadirachtin, acts by inhibiting the secretion of the molting hormone ecdysone during immature stages and also induces antifeedant and repellent effects and reduces oviposition in adults [51]. In contrast, *S. flavescens* extract contains the quinolizidine alkaloid matrine as its major active compound. Matrine interferes with neuromuscular transmission in target arthropods by affecting receptors and cholinesterase activity, ultimately resulting in neural paralysis [52, 53]. However, although botanical biopesticides are often regarded as environmentally harmless, Busatta et al. [54] demonstrated that matrine can induce ecotoxicological effects and sublethal behavioral

changes in non-target soil organisms in tropical ecosystems. The complementary effects of hormonal disruption and direct neurotoxicity provide high efficacy against economically important targets, including *B. tabaci*, *F. occidentalis*, *T. urticae*, and *S. frugiperda*, supporting the use of both bioactive compounds within Integrated Pest Management (IPM) programs [29, 30]. In addition, the commercial use of essential oils from *C. sinensis* and *M. alternifolia*, combined with *A. sativum* extract, broadens the diversity of phytosanitary modes of action and may enhance agroecosystem resilience while mitigating selection pressure for resistance in pest populations.

Finally, the consolidated findings of this study support the favorable human-health and environmental safety profiles of the biological products evaluated [5, 33]. In contrast, occupational and environmental exposure to conventional synthetic pesticides can cause endocrine disruption and has been associated with several adverse health outcomes, including diabetes [55], neurodegenerative disorders such as Parkinson's and Alzheimer's diseases [56], and reproductive and teratogenic outcomes [57]. Given their more favorable toxicological profiles, bioinputs can reduce occupational risks in agricultural settings and contribute to food production with lower synthetic pesticide residue burdens. Overall, the combination of lower chemical hazard, ecosystem integrity, and public-health protection positions these biotechnologies as strategic tools in the transition toward sustainable and resilient agrifood systems [8].

Conclusion

The five-year assessment (2019–2023) of bioinput commercialization for crops included in the Brazilian Basic Food Basket (rice, coffee, sugarcane, common bean, soybean, and wheat) in Central-Southern Brazil revealed an expanding market characterized by geographical disparities and crop-specific patterns of use. Paraná accounted for the highest sales volumes, whereas Santa Catarina showed the lowest. Although bioinputs still represent a relatively small market share compared with synthetic chemical products, their increasing adoption constitutes a strategic component of the transition toward more sustainable production of crops that are essential to Brazilian food security.

From both market and biotechnological perspectives, microbial agents were particularly prominent, especially entomopathogenic, nematophagous, and antagonistic fungi (*B. bassiana*, *M. anisopliae*, *P. lilacinum*, and *T. harzianum*) and bacteria of the genus *Bacillus*, particularly *B. thuringiensis* and *B. subtilis*, as well as multifunctional botanical extracts derived from *A. indica* and *S. flavescens*. These biological agents and phytochemicals exhibited favorable human-health and environmental hazard classifications (Environmental Hazard Class IV and GHS Category 5/Not Classified). In agricultural production, they can complement synthetic products within Integrated Pest Management (IPM) programs and represent important regulated inputs for organic and agroecological production systems.

Future efforts should prioritize continued research and robust public policies to promote the adoption and consolidation of biologically based production systems. Strengthening regulatory frameworks, together with fiscal incentives and technical support for the biological-input industry, may help reduce dependence on synthetic crop-protection products while enhancing climate resilience, food security, and biotechnological sovereignty in the transition toward sustainable agrifood systems.

Declarations

Consent to Publish

declaration: not applicable.

Ethics and Consent to Participate declarations

not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

Declaration in the manuscript: There was no funding.

Author Contribution

Marcia Orth Ripke: Conceptualization, Methodology, Data Curation, Formal Analysis, Visualization, Writing – Original Draft.Vanessa da Silva Corralo: Writing – Review & Editing.Carolina Riviera Duarte Maluche Baretta: Writing – Review & Editing.Flávio Roberto Mello Garcia: Writing – Review & Editing.All authors read and approved the final manuscript.Junir Antonio Lutinski: Conceptualization, Methodology, Data Curation, Formal Analysis, Visualization, Writing – Original Draft, Writing – Review & Editing.

Acknowledgement

The authors thank the Universidade Comunitária da Região de Chapecó (Unochapecó), particularly the Graduate Program in Health Sciences, for providing institutional support for this study.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

References

1. Brasil MAPA (2020) Decreto nº 10.375, de 26 de maio de 2020. Institui o Programa Nacional de Bioinsumos. Diário Oficial da União, Brasília. https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/decreto/d10375.htm. Accessed 31Aug 2026
2. FAO, USP-ESALQ (2024) Bioinsumos: el aliado natural para una agricultura sostenible. FAO Campus, Santiago. https://capacitacion.fao.org/theme/continuum/infocourse.php?course=221. Accessed 31Aug 2026
3. Brasil (2024) Lei nº 15.070, de 30 de dezembro de 2024. Estabelece o Marco Regulatório dos Bioinsumos no Território Nacional. Diário Oficial da União, Brasília. https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/l15070.htm. Accessed 31Aug 2026
4. Valadares-Inglis MC, Lopes RB, Faria MR (2020) Controle de artrópodes-praga com fungos entomopatogênicos. In: Fontes EMG, Valadares-Inglis MC (eds) Controle biológico de pragas da agricultura. Embrapa, Brasília, pp 201–236
5. Anvisa (2020) Nota Técnica nº 10/2020/SEI/GGTOX/DIRE3/ANVISA. Critérios para a classificação toxicológica quanto à toxicidade aguda de produtos de origem biológica de acordo com o padrão GHS estabelecido pela RDC nº 294/2019. Anvisa, Brasília. https://www.gov.br/anvisa/pt-br. Accessed 31Aug 2026
6. Hungria M, Campo RJ, Mendes IC (2001) Fixação biológica do nitrogênio na cultura da soja. Circular Técnica 35, Embrapa Soja, Londrina. https://www.embrapa.br/en/busca-de-publicacoes/-/publicacao/459673/fixacao-biologica-do-nitrogenio-na-cultura-da-soja. Accessed 31Aug 2026
7. Monnerat R, Martins ES, Praça LB, Queiroz PR, Soares CMS (2020) Controle de artrópodes-praga com bactérias entomopatogênicas. In: Fontes EMG, Valadares-Inglis MC (eds) Controle biológico de pragas da agricultura. Embrapa, Brasília, pp 237–268. http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1121825. Accessed 31Aug 2026
8. Olmo R, Wetzels SU, Armanhi JS, Arranz-Salas I, Rivera-Sánchez AO, Martínez-Arias C, Rincón-Florez VA, Araya-Cloutier C, Berg G, Sessitsch A, Compant S (2022) Microbiome research as an effective driver of success stories in agrifood systems. Frontiers in Microbiology 13:834622. https://doi.org/10.3389/fmicb.2022.834622
9. Ibama (2024) Relatório de comercialização de agrotóxicos e afins: histórico e balanço nacional. Ibama, Brasília. https://www.gov.br/ibama/pt-br/assuntos/quimicos-e-biologicos/agrotoxicos/relatorios-de-comercializacao-de-agrotoxicos. Accessed 31Aug 2026
10. Hungria M, Nogueira MA, Araújo RS (2015) Soybean seed co-inoculation with *Bradyrhizobium* spp. and *Azospirillum brasilense*: a new biotechnological tool to improve yield and sustainability. American Journal of Plant Sciences 6(6):811–817. https://doi.org/10.4236/ajps.2015.66087
11. Zilli JE, Campo RJ, Hungria M (2010) Eficácia da inoculação de *Bradyrhizobium* em pré-semeadura da soja. Pesquisa Agropecuária Brasileira 45(3):335–338. https://doi.org/10.1590/S1678-3921.pab2010.v45.7807
12. Medeiros FHV, Bettiol W (2023) Trends in translational science in biocontrol in Brazil. In: Anais do 53º Congresso Brasileiro de Fitopatologia. Sociedade Brasileira de Fitopatologia, Brasília, p 741

13. Bueno RCOF, Silva A, Gobbi AL, Santos AC, Castiglioni E (2020) Eficiência de *Bacillus subtilis* e *Trichoderma harzianum* no controle de nematoides e doenças radiculares no trigo. Summa Phytopathol 46(3):202–215. https://doi.org/10.1590/0100-5405/222105
14. Monnerat R, Práça LB, Silva ES, Montalvão SCL, Martins ES, Soares CMS, Queiroz PR (2018) Produção e controle de qualidade de produtos biológicos à base de *Bacillus thuringiensis* para uso na agricultura. Embrapa Recursos Genéticos e Biotecnologia, Brasília
15. van Lenteren JC, Bueno VHP, Luna MG, Colmenarez YC (eds) (2020) Biological control in Latin America and the Caribbean: its rich history and bright future. CABI, Wallingford. https://doi.org/10.1079/9781789242430.0000
16. Jalloh AA, Pal S, Uyi O, Malhotra P, Schmidt JM, Toews MD, Basu S (2024) Biopesticides and biological control agents: advances, integration, and prospects for sustainable pest management. Front Sustain Food Syst 8:1805083. https://doi.org/10.3389/fsufs.2024.1805083
17. CropLife Brasil (2024) O mercado de biopesticidas e bioinsumos no Brasil: balanço da safra 2023/2024. CropLife Brasil, São Paulo. https://croplifebrasil.org/mercado-de-bioinsumos-cresceu-15-na-safra-2023-2024/. Accessed 31Aug 2026
18. IPCC (2019) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva. https://www.ipcc.ch/srccl/. Accessed 31 Aug 2026
19. FAO (2021) The state of the world's land and water resources for food and agriculture – Systems at breaking point. Synthesis report 2021. Food and Agriculture Organization of the United Nations (FAO), Rome. https://doi.org/10.4060/cb7654en
20. Embrapa (2026) Seminários técnicos abordam o uso de bioinsumos na mitigação do estresse hídrico na agricultura. https://www.embrapa.br/busca-de-noticias/-/noticia/146123063/seminarios-tecnicos-abordam-o-uso-de-bioinsumos-na-mitigacao-do-estresse-hidrico-na-agricultura. Accessed 30 Aug 2026
21. Corrêa GM, Pereira CS, Queiroz ATS, Silva MP, Mello ME, Oliveira TML, Araújo LC, Frade LFS, Santos JB, Silva CM, Silva AV (2025) Use of bioinputs in sustainable agriculture: trends, challenges and perspectives for reducing the use of agrochemicals. Rev Gest Soc Ambient 19:e011955. https://doi.org/10.24857/rgsa.v19n5-117
22. Ministério do Meio Ambiente e Mudança do Clima (2024) Estratégia Nacional de Bioeconomia. MMA, Brasília. https://www.gov.br/mma/pt-br/composicao/sbc/dpeb/estrategia-nacional-de-bioeconomia. Accessed 30 Aug 2026
23. Brasil Ministério da Saúde (2014) Guia alimentar para a população brasileira, 2nd edn. Ministério da Saúde, Brasília. https://www.gov.br/agricultura/pt-br/assuntos/inspecao/produtos-vegetal/legislacao-programas-nacionais-e-seguranca-dos-alimentos-1/legislacao/legislacao-vinhos-e-bebidas/guia-alimentar-para-a-populacao-brasileira_2014.pdf/view. Accessed 30 Aug 2026
24. Brasil (2024) Decreto nº 11.936, de 5 de março de 2024. Dispõe sobre a composição da cesta básica de alimentos. Diário Oficial da União, Brasília. https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/decreto/d11936.htm. Accessed 30 Aug 2026

25. Brasil (2006) Lei nº 11.346, de 15 de setembro de 2006. Cria o Sistema Nacional de Segurança Alimentar e Nutricional – SISAN. Diário Oficial da União, Brasília. https://www.planalto.gov.br/ccivil_03/_ato2004-2006/2006/lei/l11346.htm. Accessed 30 Aug 2026
26. Fenibo EO, Ijoma GN, Matambo T (2022) Biopesticides in sustainable agriculture: current status and future prospects. In: Mandal SD, Ramkumar G, Karthi S, Jin F (eds) New and future development in biopesticide research: biotechnological exploration. Springer, Singapore, pp 1–53. https://doi.org/10.1007/978-981-16-3989-0_1
27. Ripke MO, Corralo VS, Lutinski JA (2026) Are foods of the Brazilian “staple food basket” safe for consumption? Cadernos de Saúde Pública 42:e00182325. https://doi.org/10.1590/0102-311XPT182325
28. IBGE (2026) Levantamento Sistemático da Produção Agrícola (LSPA): principais resultados - Julho 2026. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9201-levantamento-sistematico-da-producao-agricola.html. Accessed 30 Aug 2026
29. Brasil MAPA (2024) AGROFIT: Sistema de Agrotóxicos Fitossanitários. MAPA, Brasília. https://agrofit.agricultura.gov.br/. Accessed 30 Aug 2026
30. Brasil MAPA (2024) Painel e aplicativo bioinsumos. MAPA, Brasília. https://www.gov.br/agricultura/pt-br/assuntos/bioinsumos. Accessed 30 Aug 2026
31. Anvisa (2020) Monografias autorizadas. Agência Nacional de Vigilância Sanitária (Anvisa), Brasília. https://www.gov.br/anvisa/pt-br/setorregulado/regularizacao/agrotoxicos/monografias/monografias-autorizadas-por-letra. Accessed 30 Aug 2026
32. Agência Nacional de Vigilância Sanitária (Anvisa) (2021) Painel de monografias - Busca por culturas, classes e ingredientes ativos. https://www.gov.br/anvisa/pt-br/setorregulado/regularizacao/agrotoxicos/monografias. Accessed 30 Aug 2026
33. Ibama (2024) Manual de procedimentos para avaliação do potencial de periculosidade ambiental (PPA) de agentes biológicos de controle e inoculantes. Ibama, Brasília. https://www.gov.br/ibama/pt-br/assuntos/quimicos-e-biologicos/agrotoxicos/perfis-ambientais. Accessed 30 Aug 2026
34. Kynetec (2024) Uso de biológicos atinge 36% das áreas cultivadas em 2024 se mantém em crescimento no Brasil. Revista Cultivar / Kynetec Brasil. https://revistacultivar.com.br/noticias/uso-de-biologicos-atinge-36-das-areas-cultivadas-em-2024-se-mantem-em-crescimento-no-brasil. Accessed 30 Aug 2026
35. Mishra RK, Bohra A, Kamaal N, Kumar K, Gandhi K, Sujayanand GK, Saabale PR, Satheesh Naik SJ, Sarma BK, Kumar D, Mishra M, Srivastava DK, Singh NP (2018) Utilization of biopesticides as sustainable solutions for management of pests in legume crops: achievements and prospects. Egypt J Biol Pest Control 28:3. https://doi.org/10.1186/s41938-017-0004-1
36. Lengai GMW, Muthomi JW (2018) Biopesticides and their role in sustainable agricultural production. J Biosci Med 6(6):7–41. https://doi.org/10.4236/jbm.2018.66002

37. Sarma R, Adhikari K, Mahanta S, Khanikor B (2019) Combinations of plant essential oil based terpene compounds as larvicidal and adulticidal agents against *Aedes aegypti* (Diptera: Culicidae). Sci Rep 9:9471. https://doi.org/10.1038/s41598-019-45908-3
38. Meyer MC, Mazaro SM, Silva JC (eds) (2019) *Trichoderma*: uso na agricultura. Embrapa, Brasília. http://www.alice.cnptia.embrapa.br/alice/handle/doc/1117296
39. Abdel-Salam MS, Ameen HH, Soliman GM, Elkelany US, Asar AM (2018) Improving the nematicidal potential of *Bacillus amyloliquefaciens* and *Lysinibacillus sphaericus* against the root-knot nematode *Meloidogyne incognita* using protoplast fusion technique. Egyptian Journal of Biological Pest Control 28(1):31. https://www.scienceopen.com/document?vid=9cb39f29-08db-4b8a-bd8a-00c825b58348
40. Silva DM, de Souza VHM, Moral RA, Delalibera Júnior I, Mascarin GM (2022) Production of *Purpureocillium lilacinum* and *Pochonia chlamydosporia* by submerged liquid fermentation and bioactivity against *Tetranychus urticae* and *Heterodera glycines* through seed inoculation. J Fungi 8:511. https://doi.org/10.3390/jof8050511
41. Bravo A, Gómez I, Pacheco S, Soberón M (2015) Mechanism of action of Bacillus thuringiensis insecticidal toxins and their use in the control of insect pests. In: Alouf JE, Ladant D, Popoff MR (eds) The comprehensive sourcebook of bacterial protein toxins, 4th edn. Academic Press, Boston, pp 858–873. https://doi.org/10.1016/B978-0-12-800188-2.00030-6
42. Tabashnik BE, Zhang M, Fabrick JA, Wu Y, Gao M, Huang F, Wei J, Zhang J, Yelich A, Unnithan GC, Bravo A, Soberón M, Carrière Y, Li X (2015) Dual mode of action of Bt proteins: protoxin efficacy against resistant insects. Sci Rep 5:15107. https://doi.org/10.1038/srep15107
43. Borriss R (2015) *Bacillus*, a plant-beneficial bacterium. In: Lugtenberg B (ed) Principles of plant-microbe interactions: microbes for sustainable agriculture. Springer, Cham, pp 379–391. https://doi.org/10.1007/978-3-319-08575-3_40
44. Caulier S, Nannan C, Gillis A, Licciardi F, Bragard C, Mahillon J (2019) Overview of the antimicrobial compounds produced by members of the *Bacillus subtilis* group. Front Microbiol 10:302. https://doi.org/10.3389/fmicb.2019.00302
45. Shahid I, Han J, Hanooq S, Malik KA, Borchers CH, Mehnaz S (2021) Profiling of metabolites of *Bacillus* spp. and their application in sustainable plant growth promotion and biocontrol. Front Sustain Food Syst 5:605195. https://doi.org/10.3389/fsufs.2021.605195
46. Gutiérrez-Mañero FJ, Ramos-Solano B, Probanza A, Mehouachi J, Tadeo FR, Talon M (2001) The plant-growth-promoting rhizobacteria *Bacillus pumilus* and *Bacillus licheniformis* produce high amounts of physiologically active gibberellins. Physiol Plant 111(2):206–211. https://doi.org/10.1034/j.1399-3054.2001.1110211.x
47. Bilal M, Achard C, Barbe F, Chevaux E, Ronholm J, Zhao X (2021) *Bacillus pumilus* and *Bacillus subtilis* promote early maturation of cecal microbiota in broiler chickens. Microorganisms 9(9):1899. https://doi.org/10.3390/microorganisms9091899
48. Ji ZL, Peng S, Chen LL, Liu Y, Yan C, Zhu F (2020) Identification and characterization of a serine protease from *Bacillus licheniformis* W10: a potential antifungal agent. Int J Biol Macromol 145:594–603. https://doi.org/10.1016/j.ijbiomac.2019.12.216

49. Muras A, Romero M, Mayer C, Otero A (2021) Biotechnological applications of *Bacillus licheniformis*. Crit Rev Biotechnol 41(4):609–627. https://doi.org/10.1080/07388551.2021.1873239
50. Martínez-Balerdi M, Caballero J, Aguirre E, Caballero P, Beperet I (2025) Baculoviruses as microbial pesticides: potential, challenges, and market overview. Viruses 17(7):917. https://doi.org/10.3390/v17070917
51. Campos EVR, de Oliveira JL, Pascoli M, de Lima R, Fraceto LF (2016) Neem oil and crop protection: from now to the future. Front Plant Sci 7:1494. https://doi.org/10.3389/fpls.2016.01494
52. Wu J, Yu X, Wang X, Tang L, Ali S (2019) Matrine enhances the pathogenicity of *Beauveria brongniartii* against *Spodoptera litura* (Lepidoptera: Noctuidae). Frontiers in Microbiology 10:1812. https://doi.org/10.3389/fmicb.2019.01812
53. Wu J, Yang B, Zhang X, Cuthbertson AGS, Ali S (2021) Synergistic interaction between the entomopathogenic fungus *Akanthomyces attenuatus* (Zare & Gams) and the botanical insecticide Matrine against *Megalurothrips usitatus* (Bagrall). Journal of Fungi 7:536. https://doi.org/10.3390/jof7070536
54. Busatta E, Bandeira FO, Ogliari AJ, Ribeiro LP, Alves PRL, Baretta D, Baretta CRDM (2026) Ecotoxicological effects of a matrine-based botanical insecticide on edaphic invertebrates in a tropical soil. Applied Soil Ecology 223:107096. https://doi.org/10.1016/j.apsoil.2026.107096
55. Velmurugan G, Ramprasath T, Gilles M, Swaminathan K, Ramasamy S (2017) Gut microbial degradation of organophosphate insecticides-induces glucose intolerance via gluconeogenesis. Genome Biol 18:33. https://doi.org/10.1186/s13059-016-1134-6
56. Dorsey ER, Bloem BR (2024) Parkinson's disease is predominantly an environmental disease. Journal of Parkinson's Disease 14(3):451–465. https://doi.org/10.3233/JPD-230357
57. Martenies SE, Perry MJ (2013) Environmental and occupational pesticide exposure and human sperm parameters: a systematic review. Toxicology 307:66–73. https://doi.org/10.1016/j.tox.2013.02.005

Figures

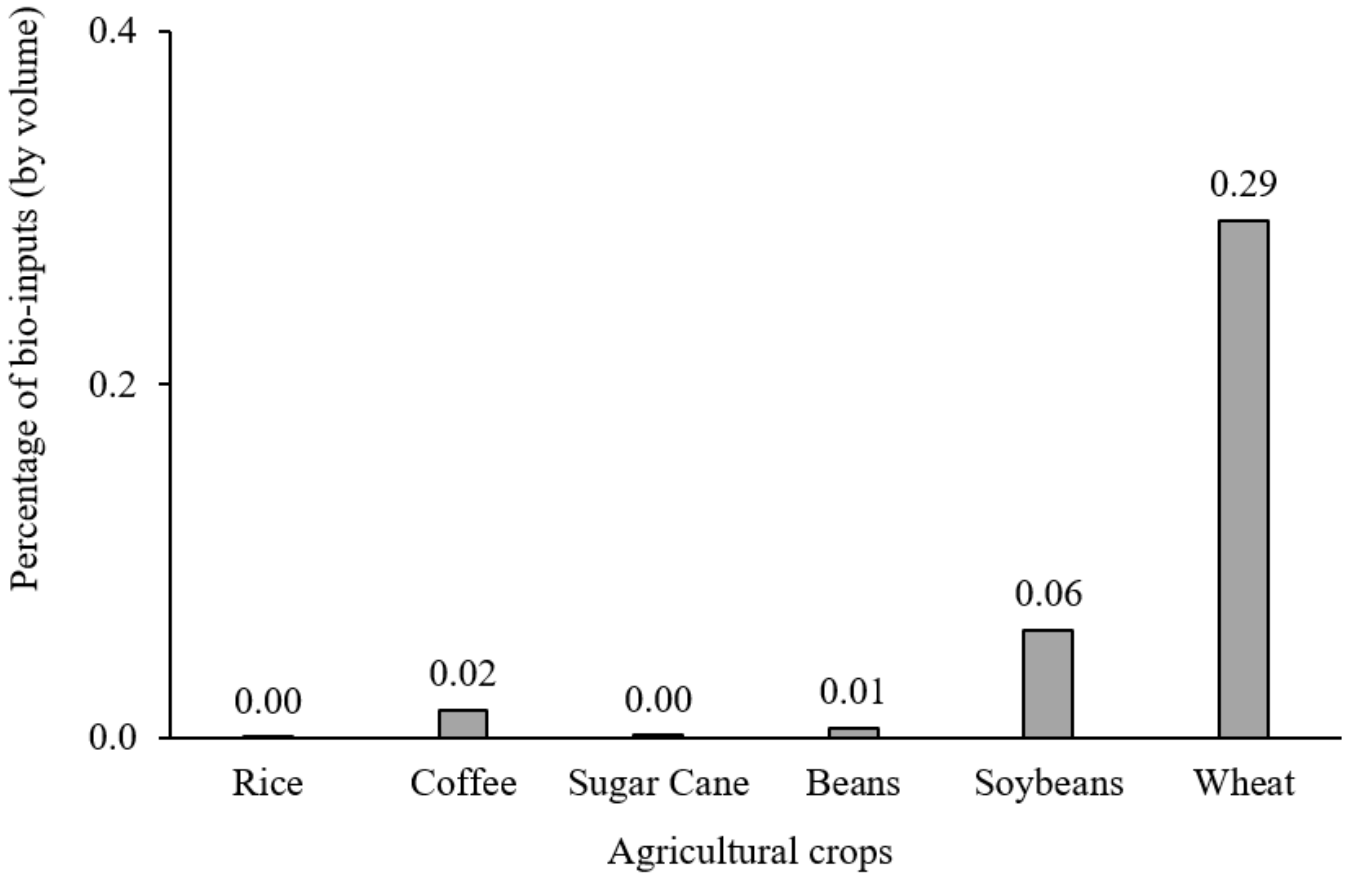


Figure 1

Percentage of bioinputs relative to the total volume of active ingredients (synthetic and biological) commercialized by crop in Central-Southern Brazil (2019–2023). Note**:** Data compiled by the authors from official pesticide and bioinput commercialization records provided by INDEA (Mato Grosso), ADAPAR (Paraná), SEAPI (Rio Grande do Sul), and CIDASC (Santa Catarina) (2019–2023).

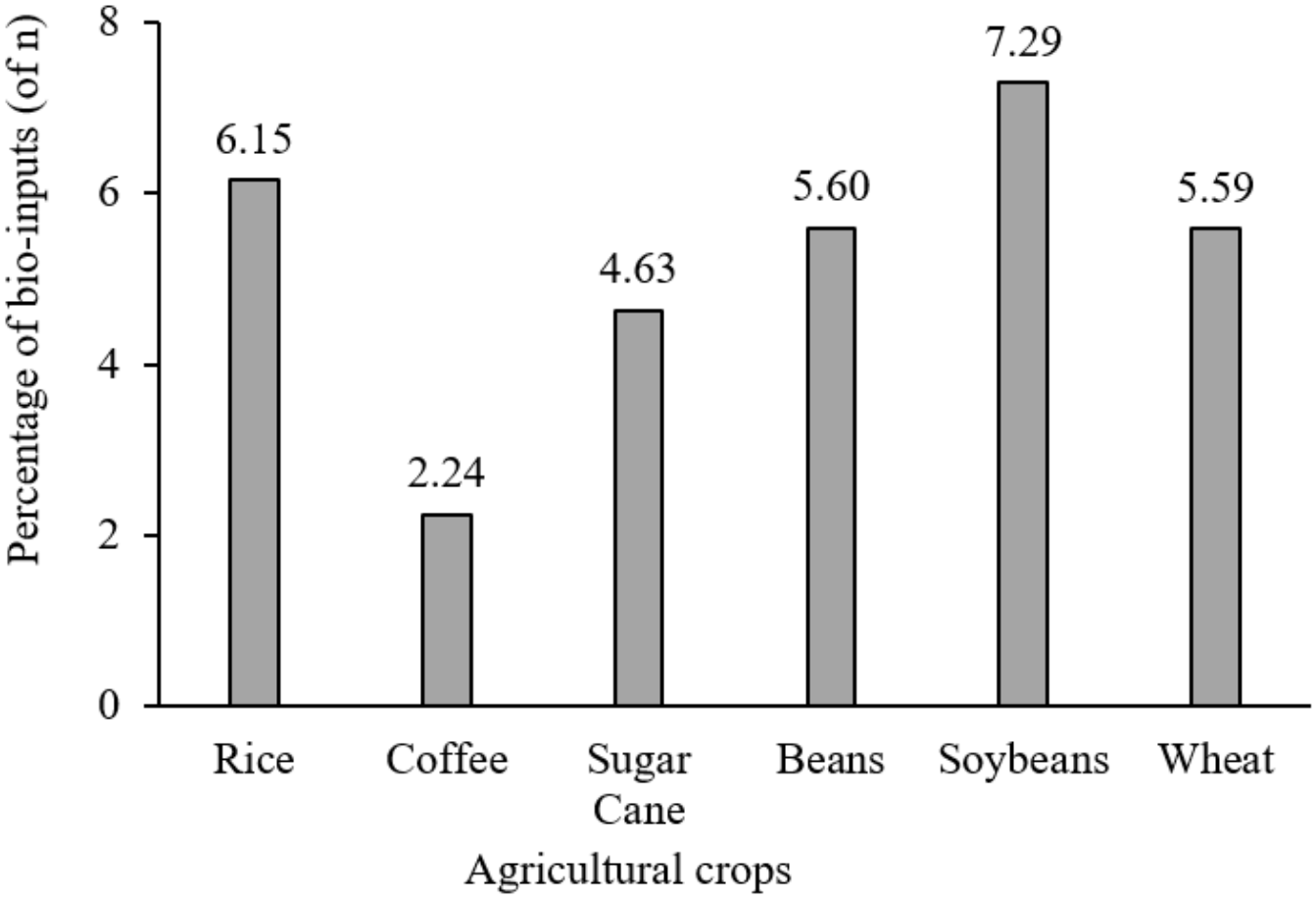


Figure 2

Relative contribution of the diversity of biological active ingredients commercialized by crop in Central-Southern Brazil (2019–2023). Note: Data compiled by the authors from official pesticide and bioinput commercialization records provided by INDEA (Mato Grosso), ADAPAR (Paraná), SEAPI (Rio Grande do Sul), and CIDASC (Santa Catarina) (2019–2023).