Biological management of *Heterodera glycines* in soybean: How the use of microbial products has reshaped nematode control strategies

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ABSTRACT. Soybean (*Glycine max* (L.) Merrill) is one of Brazil's most important agricultural crops, playing a key economic and strategic role in agribusiness. However, its productivity is continually threatened by plant-parasitic nematodes, especially *Heterodera glycines*, which cause significant yield losses. Given the limitations of chemical control and the growing demand for sustainable practices, bioinputs have emerged as a viable alternative for managing this pathogen. This study reviews biological control strategies against *H. glycines* using beneficial microorganisms such as fungi and bacteria. The findings show that agents such as *Purpureocillium lilacinum*, *Pochonia chlamydosporia*, *Bacillus* spp., and *Trichoderma* spp. are effective in suppressing nematode populations, promoting plant growth, and improving soil health. The integration of these bioinputs with other practices, including the use of resistant cultivars and crop rotation, is essential for the success of integrated pest management in soybean cultivation.

Key words: cyst nematode, bioinputs, biological control, nematodes, soybean.

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INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) ranks among the world's most strategically important agricultural commodities, underpinning global food security, livestock feed chains, and bioenergy systems. Its cultivation traces back to East Asia, with China recognized as the center of origin (Morse, 1950). From there, the crop spread to Korea, Japan, and eventually Europe by the early 18th century, following botanical accounts of its dietary use in Japan (Piper & Morse, 1923; Probst & Judd, 1973). Commercial cultivation in the United States was established around 1765, accompanied by progressive advances in yield and cultivar development (Piper & Morse, 1923; Probst & Judd, 1973; Gazzoni, 2018).

In Brazil, soybean was first recorded in 1882 in the state of Bahia by Gustavo D'Utra, though early varieties were poorly adapted to tropical conditions (Gazzoni, 2018). Commercial expansion began in Rio Grande do Sul, whose temperate climate initially favored cultivation (Bonato & Bonato, 1987). The decisive leap occurred from the 1970s onward, when breeding programs and public policy enabled the development of cultivars adapted to low-latitude regions between the Tropic of Capricorn and the Equator, transforming the Brazilian Cerrado into one of the world's most productive agricultural frontiers (Embrapa, 2024). Brazil is currently the world's largest soybean producer and exporter, accounting for nearly 50% of world trade. In the 2024/25 season, national production is estimated at 169.7 million tons (a 14.8% increase over the previous cycle) with Mato Grosso leading at 51 million tons and Goiás reaching a record 20.4 million tons (CONAB, 2025a; CONAB, 2025b; Goiás, 2025; Agência Brasil, 2025).

Despite this productive dominance, soybean yields are systematically threatened by a wide range of phytosanitary constraints. Fungal diseases such as Asian soybean rust (*Phakopsora pachyrhizi*), white mold (*Sclerotinia sclerotiorum*), target spot (*Corynespora cassiicola*), and Phytophthora root rot (*Phytophthora sojae*) impose substantial losses annually (Godoy et al., 2016; Soares et al., 2023). Among biotic stressors, however, plant-parasitic nematodes stand out for their cryptic nature, high reproductive potential, and increasing difficulty of control, having emerged as one of the most economically damaging groups affecting the crop in Brazil and worldwide.

These soil-dwelling microscopic organisms parasitize plant roots, impairing water and nutrient absorption and causing stunting, chlorosis, and significant yield reductions (Embrapa, 2020). Annual losses attributed to nematodes in Brazilian agribusiness are estimated at BRL 35 billion, of which BRL 16.2 billion are linked to soybean alone (SNA, 2015). During the 2023/24 crop season, nematode-control treatments were applied to 17 million ha of soybean (Revista Cultivar, 2025), reflecting the severity of infestation pressure across producing regions. In heavily infested fields, productivity losses can exceed 50%, and if current management conditions persist, cumulative losses across crops may surpass BRL 870 billion within ten years (Syngenta, Agroconsult, & SBN, 2022).

The most economically relevant species include *Heterodera glycines* (soybean cyst nematode, SCN), *Pratylenchus brachyurus* (root lesion nematode), *Meloidogyne incognita* and *M. javanica* (root-knot nematodes), and *Rotylenchulus reniformis* (reniform nematode) (Santos, Bellé, & Verssiani, 2025). These species are broadly distributed across Brazilian soybean-producing regions, with high adaptive capacity that complicates management and amplifies economic impact (Dias et al., 2010; Asmus & Inomoto, 2014). Damage manifests through root galling, necrosis, syncytium formation, and predisposition to secondary infections by *Fusarium* spp. and *Rhizoctonia solani*, intensifying the root-disease complex (Carneiro et al., 2020).

Among these, *H. glycines*, first reported in Brazil during the 1991/92 season, is considered the most damaging nematode species to soybean, owing to its high fecundity, genetic variability, and capacity to overcome host resistance (Mendes & Dickson, 1993; Niblack et al., 2002; Rocha & Dias-Arieira, 2023). Its life cycle spans 24 to 30 days, enabling multiple generations per growing season. The infective second-stage juvenile (J2) penetrates soybean roots, migrates to the vascular cylinder, and induces the formation of syncytia, specialized multinucleate feeding sites that continuously extract photosynthates, impairing root function and reducing yield potential (Rocha & Dias-Arieira, 2023). Globally, several HG Types of *H. glycines* have been reported, with HG Types 1, 3, 4, 6, 9, and 14 already identified in Brazil. HG Type 14 has been frequently reported in Brazilian soybean-producing regions and is considered highly adapted to local production systems (Rocha & Dias-Arieira, 2023). The existence of multiple HG Types directly undermines resistance-based management strategies, as selection pressure from resistant cultivars favors the emergence of virulent populations over successive seasons (Ferraz & Brown, 2016).

Field symptoms are frequently nonspecific, resembling nutrient deficiencies or drought stress, and include foliar chlorosis, stunting, and irregular patches of reduced plant stand (commonly termed "hotspots") associated with high nematode population densities (Dias et al., 2010; Carneiro et al., 2020). Dissemination occurs primarily through passive transport of cysts adhering to machinery, vehicles, or footwear, and through irrigation or surface runoff (Dias et al., 2010; Carneiro et al., 2020).

Conventional management of *H. glycines* relies on the integration of resistant cultivars, crop rotation with non-host species (corn, sorghum, millet), and rational use of chemical nematicides. However, each strategy carries inherent limitations: resistant cultivars are subject to HG Type shifts; rotation is constrained by regional cropping systems and market pressures; and chemical nematicides entail economic costs, environmental risks, and residue concerns (Dias et al., 2010; Ferraz & Brown, 2016; Carneiro et al., 2020). These limitations underscore the urgent need for complementary, sustainable tools within integrated nematode management (INM) programs.

Biological control using microbial bioinputs has emerged as a scientifically robust and practically viable component of INM for *H. glycines*. The main microorganisms applied include fungi such as *Purpureocillium lilacinum* (formerly *Paecilomyces lilacinus*), *Pochonia chlamydosporia*, and *Trichoderma* spp., and bacteria of the genera *Bacillus* (notably *B. subtilis*, *B. velezensis*, and *B. amyloliquefaciens*) and *Pasteuria* spp. These agents act through multiple, complementary mechanisms: (i) direct parasitism of eggs, juveniles, females, and cysts; (ii) production of nematicidal metabolites, including lipopeptides, chitinases, proteases, and volatile organic compounds; (iii) rhizosphere colonization and competition for space and nutrients; and (iv) induction of systemic resistance in the host plant (Ferraz & Brown, 2016). In Brazil, several products based on these microorganisms are already registered with the Department of Agriculture, Livestock and Food Supply (MAPA) for nematode management in soybean, and the bionematicide market reached approximately BRL 1.15 billion in 2023, biological products have gained substantial market share in soybean nematode management (Bettiol & Medeiros, 2023). Experimental evidence supports their efficacy: *Bacillus* strains have caused up to 93.8% mortality of J2 juveniles under greenhouse conditions (Zhou et al., 2024), while combined applications of *Purpureocillium* sp., *B. subtilis*, *Pochonia* sp., and *Trichoderma asperellum* significantly reduced *H. glycines* populations compared to conventional management

(Silva, K. C. L., et al., 2022). Field studies indicate population reductions ranging from 30% to 70% depending on the product, application method, and edaphoclimatic conditions, with some treatments additionally promoting root and shoot biomass and stabilizing grain yield (Dias-Arieira et al., 2023).

Thus, integrating genetic, cultural, chemical, and biological measures constitutes the most effective framework for managing *H. glycines* in soybean. Microbial bioinputs are increasingly consolidated as indispensable tools within this framework, reducing dependency on chemical nematicides while meeting the growing demand for sustainable and resilient agricultural systems. This review therefore examines the main biological control strategies for *H. glycines* using microbial bioinputs, with emphasis on the microorganisms involved, their mechanisms of action, registered products, efficacy under field and greenhouse conditions, and contributions to sustainable soybean management.

MATERIALS AND METHODS

This study constitutes a descriptive and integrative literature review on the biological management of *Heterodera glycines* in soybean, with emphasis on microbial bioinputs, their mechanisms of action, registered products, and efficacy under experimental and field conditions.

Literature searches were conducted between April and September 2025 across peer-reviewed scientific databases and technical repositories, including the CAPES Journals Portal, SciELO, Google Scholar, and the Embrapa Digital Library, complemented by specialized technical sources such as Revista Cultivar and Mais Soja. The following keywords and Boolean combinations were used in Portuguese and English: "soybean nematodes," "*Heterodera glycines*," "nematode management," "soybean yield losses," "nematodes in Brazil," "biological control," and "biological agents in agriculture."

Eligible documents included peer-reviewed scientific articles, technical bulletins, institutional publications from Embrapa, and credible extension materials. Inclusion criteria were: (i) direct relevance to *Heterodera glycines* biology, epidemiology, or management; (ii) publication in indexed journals or by recognized institutional sources; and (iii) availability of full text. Documents addressing other nematode species without comparative data involving *Heterodera glycines*, or those lacking methodological transparency, were excluded. The temporal scope ranged from 1923 to 2025, encompassing the earliest historical records of soybean cultivation through the most recent advances in biological control. Data on registered microbiological nematicides were obtained from the MAPA AGROFIT system, consulted in July 2025 (Alves & Ferreira, 2025). Data synthesis was conducted in a descriptive and integrative manner, aiming to critically map the current state of knowledge and identify research gaps and practical opportunities for the sustainable management of *Heterodera glycines* in Brazilian soybean systems.

RESULTS AND DISCUSSION

Mechanisms of action of biological control agents

Biological control of *H. glycines* has advanced considerably through the use of different groups of microorganisms, each exhibiting specific and often complementary modes of action. The main groups studied and commercially registered include nematophagous fungi, plant growth-promoting rhizobacteria (PGPR), and specialized endoparasitic bacteria. Understanding these mechanisms is essential for designing rational, effective biological management programs.

Nematophagous fungi represent one of the most studied groups, acting primarily through direct parasitism of eggs and juveniles. *P. chlamydosporia* produces appressoria and penetration hyphae that breach the eggshell, subsequently secreting chitinolytic and proteolytic enzymes (including serine proteases and chitinases) that degrade structural components of the egg and immobilize juveniles (Kerry, 2000). *P. lilacinum* (formerly *P. lilacinus*) exhibits analogous enzymatic activity and has demonstrated reductions in egg and juvenile populations of up to 60% under controlled conditions (Dias-Arieira et al., 2023). Under greenhouse conditions, *P. chlamydosporia* and *P. lilacinum* isolates produced from submerged liquid fermentation significantly reduced *H. glycines* population density in soybean roots, confirming their viability as seed treatment agents (Ferraz & Brown, 2016; Silva, D. M., et al., 2022). *Trichoderma* spp. act through a broader mechanistic spectrum: in addition to mycoparasitism and antibiosis via volatile and non-volatile secondary metabolites (including trichomycin, gliotoxin, viridin, chitinases, and β-1,3-glucanases), these fungi colonize the rhizosphere and trigger induced systemic resistance (ISR) in host plants (Yao et al., 2023). Specifically, fermentation broths of *T. hamatum* HZ-9 and *T. virens* HZ-L9 inhibited *H. glycines* egg hatching at rates of 80.6% and 79.4%, respectively, demonstrating direct suppressive activity against the soybean cyst nematode (Contina et al., 2017; Yao et al., 2023; Reyes-Pérez et al., 2025). Furthermore, *Trichoderma* spp. have demonstrated efficacy against cyst-forming nematodes of the genera *Heterodera* and *Globodera* through direct egg and juvenile parasitism mediated by chitinase and protease secretion (Reyes-Pérez et al., 2025).

Among bacteria, *Bacillus* spp. constitutho the most commercially relevant group for *H. glycines* management in Brazil. *B. subtilis*, *B. velezensis*, and *B. amyloliquefaciens* produce a diverse arsenal of bioactive compounds (including iturin, fengycin, surfactin, and other lipopeptides) with demonstrated nematicidal activity against second-stage juveniles (J2) (Iftikhar et al., 2024). These bacteria also colonize root surfaces, forming competitive biofilms that limit nematode access to the rhizosphere, and produce hydrolytic enzymes (chitinases, proteases, and glucanases) that degrade cuticular and eggshell structures. Under greenhouse conditions, *Bacillus* strains caused up to 93.8% mortality of *H. glycines* J2 juveniles, underscoring their potential as primary components of bionematicide formulations (Zhou et al., 2024). Beyond direct nematicidal activity, *Bacillus*-based products consistently promote plant growth by enhancing nutrient solubilization, producing phytohormones such as indole-3-acetic acid (IAA), and stimulating systemic resistance pathways (Iftikhar et al., 2024).

P. nishizawae represents a unique and highly specific biological control agent. This obligate endoparasitic bacterium adheres its endospores to the cuticle of J2 juveniles, penetrates the nematode body, and undergoes internal sporulation, resulting in host death prior to reproduction. Its extreme host specificity for *H. glycines* makes it particularly attractive for targeted biocontrol programs, although this same specificity limits its broad-spectrum applicability and complicates mass production (Noel, Atibalentja, & Stirling, 2005; Kessler & Koehler, 2023).

Microbial consortia combining fungi and bacteria have demonstrated synergistic suppressive effects that exceed those of individual agents. Combined applications of *Purpureocillium* sp., *B. subtilis*, *Pochonia* sp., and *T. asperellum* significantly reduced *H. glycines* populations relative to conventional chemical management under field conditions (Silva, K. C. L., et al., 2022). The mechanistic basis for synergism lies in the complementarity of action: while fungi target eggs and early juveniles, bacteria suppress mobile J2 stages and trigger systemic plant defenses, collectively disrupting multiple points of the nematode life cycle (Rocha & Dias-Arieira, 2023). The efficacy of biological control agents is modulated by edaphoclimatic factors, including soil texture, pH, organic matter content, temperature, and moisture, as well as by the initial nematode population density and the diversity of *H. glycines* HG Types present (Rocha & Dias-Arieira, 2023). Other examples of microorganisms and their mechanisms of action used in *H. glycines* management are summarized in Table 1.

Registered bionematicides and market context

The expansion of biological control as a management tool for *H. glycines* in Brazil is clearly reflected in the regulatory landscape. According to a survey conducted in July 2025 in the MAPA AGROFIT system, there are currently 111 microbiological nematicide products registered, covering 11 nematode species, produced by 36 companies, based on 21 microbial species, 16 bacteria and 5 fungi (Alves & Ferreira, 2025).

Of these, 45 products are specifically registered for *H. glycines* management, the third highest number among all nematode species, surpassed by *P. brachyurus* (76 products) and *M. incognita* (68 products), and closely followed by *M. javanica* (44 products) (Alves & Ferreira, 2025). This regulatory volume demonstrates that *H. glycines* is among the primary targets of the Brazilian bionematicide industry.

The active ingredients registered for *H. glycines* management encompass a diverse microbial portfolio. Among bacteria, *B. amyloliquefaciens* leads with 16 registered products, followed by *B. subtilis* (13), *B. velezensis* (8), *B. firmus* (4), *B. thuringiensis* (2), *P. nishizawae* (2), *Burkholderia rinojensis* (2), *Pseudomonas oryzihabitans* (1), and *P. glycinis* (1). Among fungi, *P. lilacinum* accounts for 11 products, *T. harzianum* for 6, *P. chlamydosporia* for 5, *T. asperellum* for 2, and *T. endophyticum* for 1 (Alves & Ferreira, 2025). Multi-strain consortia (combining two or more *Bacillus* species, or bacteria with fungi) represent a significant portion of registered formulations, reflecting the industry's recognition of synergistic suppression as a commercial strategy.

Among the products specifically registered for *H. glycines*, notable examples include Clariva PN and Clariva PN BR (Syngenta), based on *P. nishizawae*, the only obligate endoparasitic bacterium registered exclusively for SCN management; Arvatico and Certano (Syngenta), based on *B. velezensis*; Andril Prime and Votivo Prime (BASF), based on *B. firmus*; Lalnix Resist (Lallemand), based on *T. endophyticum*; T-Protec (Andermatt do Brasil), based on *T. asperellum*; and SuperShield (Superbac), a multi-strain consortium of *B. subtilis*, *B. velezensis*, *B. amyloliquefaciens*, and *B. licheniformis* (Alves & Ferreira, 2025). The majority of products are registered for seed treatment (TS), in-furrow application, or both, facilitating integration into standard soybean production systems. Several products also permit drench and spray applications, expanding flexibility within integrated management programs.

Table 1. Biocontrol agents and their respective modes of action reported for the management of *Heterodera glycines.*

Microorganism	Mode of Action
Bacillus subtilis	Production of antimicrobial metabolites (iturin, surfactin, fengycin); competition for space and nutrients; induction of systemic resistance in plants
Bacillus velezensis	Production of lipopeptides, antibiotics, and hydrolytic enzymes; rhizosphere colonization; systemic resistance induction
Bacillus amyloliquefaciens	Production of antimicrobial compounds; antibiosis; rhizosphere colonization; systemic resistance induction
Bacillus firmus	Production of chitinolytic and proteolytic enzymes that degrade eggs and juveniles; direct effect on nematode cuticle
Bacillus thuringiensis	Production of Cry and Cyt toxins acting against nematode juveniles
Bacillus licheniformis	Production of hydrolytic enzymes and nutrient competition in the rhizosphere
Purpureocillium lilacinum (Paecilomyces lilacinus)	Direct parasitism of eggs and juveniles; enzymatic degradation of eggshells via chitinases and serine proteases
Pochonia chlamydosporia	Egg parasitism through chitinolytic enzyme activity; endophytic colonization and ISR induction
Trichoderma harzianum	Mycoparasitism, antibiosis, competition, and induction of systemic resistance; inhibition of SCN egg hatching
Trichoderma asperellum	Parasitism, antifungal and nematicidal metabolite production, and ISR induction
Trichoderma endophyticum	Endophytic colonization, competition for rhizosphere space, and systemic resistance induction
Pasteuria nishizawae	Obligate endoparasitic bacterium; endospore adhesion to J2 cuticle, penetration, and internal destruction prior to reproduction
Pseudomonas oryzihabitans	Siderophore production, antibiosis, and systemic resistance induction
Pseudomonas glycinis	Rhizosphere colonization; antimicrobial metabolite production; resistance induction
Burkholderia rinojensis	Production of toxins and antimicrobial metabolites; root colonization
Priestia megaterium (Bacillus megaterium)	Enzyme production; plant-growth stimulation; systemic resistance induction
B. subtilis + B. licheniformis	Antimicrobial metabolite and enzyme production; competition; rhizosphere colonization
B. subtilis + T. harzianum	Combined antibiosis, mycoparasitism, ISR induction, and root colonization
B. subtilis + B. velezensis	Production of antimicrobial metabolites, lipopeptides, and enzymes with strong rhizosphere colonization
B. subtilis + B. paralicheniformis	Antimicrobial metabolite production; root colonization; nutrient competition
B. subtilis + B. thuringiensis	Combined antibiosis and Cry/Cyt toxin production targeting juveniles
B. velezensis + B. amyloliquefaciens	Lipopeptide and enzyme production with intense rhizosphere colonization
B. subtilis + B. amyloliquefaciens	Antimicrobial metabolite production; systemic resistance induction
B. subtilis + B. licheniformis + P. lilacinum	Antibiosis, competition, egg parasitism, and systemic resistance induction
B. velezensis + B. amyloliquefaciens + B. thuringiensis	Lipopeptide, metabolite, and Cry/Cyt toxin production; root colonization
B. subtilis + B. licheniformis + B. circulans + Paenibacillus azotofixans	Metabolite and enzyme production; biological N fixation; improved plant vigor
B. subtilis + T. asperellum + P. lilacinum	Combined antibiosis, mycoparasitism, egg parasitism, and systemic resistance induction

Source: Adapted from Agrofit/MAPA (2025); Alves & Ferreira (2025).

Notably, many registered bionematicides also carry approval for simultaneous control of important soil-borne fungal pathogens (including *F. solani* f.sp. *glycines*, *R. solani*, *Macrophomina phaseolina*, and *S.*

sclerotiorum), reinforcing their multifunctional value and their role in reducing overall chemical input dependency (Alves & Ferreira, 2025). The bionematicide market in Brazil reached approximately BRL 1.15 billion in 2023, with biological products already representing around 94% of nematicide sales for soybean, a historic milestone that consolidates biological control as the dominant management strategy for nematodes in the country (Bettiol & Medeiros, 2023).

Field efficacy and agronomic benefits

The application of microbial bioinputs for *H. glycines* management has consistently demonstrated significant reductions in nematode population densities under experimental and commercial field conditions. In trials involving *Bacillus* spp., *Trichoderma* spp., and *P. lilacinum*, egg and juvenile counts were reduced by 40% to 70% relative to untreated controls, with efficacy conditioned by product, dosage, and application timing (Rocha & Dias-Arieira, 2023). Preventive application (particularly as seed treatment or in-furrow at planting) consistently yielded superior results compared with curative applications, in agreement with the epidemiological dynamics of *H. glycines*, whose peak infection occurs during early root development stages (Rocha & Dias-Arieira, 2023).

Biological treatments also promoted significant agronomic benefits beyond nematode suppression. Increases in shoot and root biomass were recorded across multiple studies, attributed to the plant growth-promoting properties of *Bacillus*-based formulations, including IAA production, phosphate solubilization, and ISR activation (Iftikhar et al., 2024; Viana, 2024). Significant grain yield increases were reported in plots receiving biological treatments, confirming the dual nematicidal and growth-promoting value of these products within integrated management programs (Xiang et al., 2017; Zhou et al., 2024). The stability of these results across diverse edaphoclimatic conditions reinforces the strategic role of bioinputs as cornerstones of sustainable *H. glycines* management.

Nematode control in soybean has traditionally relied on chemical nematicides, which provide immediate but short-term effects and are often associated with high costs and environmental impacts. In contrast, bioinputs exhibit multiple complementary mechanisms (toxic metabolite production, rhizosphere colonization and competition, direct parasitism of eggs and juveniles, and ISR induction) that confer greater persistence and cumulative soil effects compared with chemical nematicides, whose activity declines rapidly after application (Timper, 2014; Ferraz & Brown, 2016). From an environmental standpoint, bio-based products show high selectivity, preserving beneficial soil microbiota, a critical advantage, since microbial diversity is directly related to soil health and agroecosystem resilience (Embrapa, 2020). Moreover, because bioinputs act through multiple and diverse mechanisms, they reduce selection pressure on *H. glycines* populations, lowering the risk of resistance development, a persistent concern with repeated use of chemical molecules sharing the same mode of action (Rocha & Dias-Arieira, 2023).

Integration with genetic resistance and cultural practices

Biological control delivers optimal results when integrated with complementary management strategies. Soybean genotypes carrying resistance sources such as PI 88788 and Peking exhibit enhanced tolerance to *H. glycines* infection and are widely recommended in infested production systems (Mitchum, 2016). According to a survey conducted in July 2025, 126 soybean varieties registered in Brazil present some level of resistance to at least one of the 11 recognized HG Types of *H. glycines*, with 14 varieties showing resistance to more than five HG Types (Alves & Ferreira, 2025). However, continuous and exclusive reliance on a single resistance source exerts strong selection pressure on nematode populations, favoring the emergence of virulent HG Types capable of overcoming host resistance, a phenomenon well-documented in Brazil, where HG Type 14 has become dominant (Ferraz & Brown, 2016; Rocha & Dias-Arieira, 2023). Rotating resistance sources in combination with biological agents reduces this selection pressure and extends the productive lifespan of available resistant cultivars.

Crop rotation with non-host species (including corn (*Zea mays*), sorghum (*Sorghum bicolor*), brachiaria (*Urochloa* spp.), and *Crotalaria* spp.) remains a critical cultural tool for reducing soil *H. glycines* population densities between soybean seasons (Rocha & Dias-Arieira, 2023). The integration of rotation with biological agents and resistant cultivars within a structured INM framework has demonstrated consistent population suppression and yield stabilization across multiple studies (Silva et al., 2022). This multi-tactic approach aligns with the conceptual principles of Integrated Pest Management (IPM) and represents the most resilient and economically viable strategy for the long-term management of *H. glycines* in Brazilian soybean systems. Bioinputs, therefore, should not be viewed merely as chemical substitutes, but as essential and complementary tools within an integrated management system that balances productivity, profitability, and environmental sustainability.

CONCLUSION

H. glycines remains one of the most economically damaging biotic constraints to soybean production in Brazil, and its management demands a multitactic, science-based approach that transcends the limitations of any single control strategy. This review confirms that microbial bioinputs, including *P. lilacinum*, *P. chlamydosporia*, *Bacillus* spp., *Trichoderma* spp., and *P. nishizawae*, represent technically sound, environmentally safe, and commercially viable components of integrated nematode management (INM) programs. These agents act through complementary and multi-site mechanisms, encompassing direct parasitism of eggs and juveniles, production of nematicidal metabolites, rhizosphere colonization and competition, and induction of systemic resistance in host plants, a mechanistic diversity that confers cumulative suppressive effects and reduces the likelihood of resistance evolution in nematode populations.

The regulatory consolidation of biological control in Brazil is unequivocal: as of July 2025, 111 microbiological nematicide products are registered with MAPA, based on 21 microbial species and produced by 36 companies, with 45 products specifically indicated for *H. glycines* management. This portfolio, combined with a bionematicide market that reached BRL 1.15 billion in 2023, reflects the growing confidence of producers, industry, and regulatory bodies in the efficacy and safety of bio-based nematode control.

Nevertheless, the field performance of bioinputs remains conditioned by edaphoclimatic factors, soil microbiota composition, application timing, initial nematode population density, and the diversity of *H. glycines* HG Types present. These variables underscore the need to embed biological control within structured INM frameworks that integrate resistant cultivars (with rotation of resistance sources to mitigate virulence selection), crop rotation with non-host species, sound soil-health practices, and rational use of chemical nematicides where warranted. The synergistic interaction among these components delivers greater result consistency than any strategy applied in isolation.

From a broader perspective, the consolidation of biological control for *H. glycines* aligns with global trends toward sustainable agricultural systems, reduced pesticide residues, and enhanced agroecosystem resilience, demands increasingly imposed by international commodity markets. Advancing this agenda will require continued investment in applied research to validate bioinput efficacy across the diverse edaphoclimatic regions of Brazilian soybean production, development of improved formulations with enhanced environmental stability, refinement of diagnostic and population monitoring protocols, and strengthening of technical training at the farm level. The convergence of applied science, regulatory progress, and field-level management capacity will determine the pace at which biological control fulfills its potential as a cornerstone of sustainable *H. glycines* management in Brazilian soybean systems.

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