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USE OF BIOINPUTS IN BLACK PEPPER (*PIPER NIGRUM L.*) AND LIVE STAKES WITH GLIRICIDIA SEPIUM: A SYSTEMATIC REVIEW OF EFFECTS ON NUTRITION, HEALTH, AND PRODUCTIVITY

USO DE BIOINSUMOS NA PIMENTA-DO-REINO (*PIPER NIGRUM L.*) E TUTOR VIVO COM GLIRICIDIA SEPIUM: REVISÃO SISTEMÁTICA DE EFEITOS SOBRE NUTRIÇÃO, SANIDADE E PRODUTIVIDADE

USO DE BIOINSUMOS EN LA PIMIENTA NEGRA (*PIPER NIGRUM L.*) Y ESTACAS VIVAS CON GLIRICIDIA SEPIUM: UNA REVISIÓN SISTEMÁTICA SOBRE LOS EFECTOS EN LA NUTRICIÓN, LA SALUD Y LA PRODUCTIVIDAD

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ABSTRACT

Bio-inputs have become vital in agriculture, helping to boost productivity, improve soil health, reduce greenhouse gases, and lower production costs. This systematic review summarizes the evidence on using bio-inputs in black pepper (*Piper nigrum* L.) cultivation, focusing specifically on the live stake system with *Gliricidia sepium*. Fourteen primary studies (1985–2025) were included after searching five scientific databases following PRISMA 2020 guidelines. The evidence shows that *Azospirillum* can cut mineral nitrogen fertilization by up to 25% without affecting yield. *Bacillus* and *Trichoderma* are key in controlling soil-borne pathogens, while live stakes with *Gliricidia sepium* lowered establishment costs by about 27% while keeping crop productivity steady. However, important gaps still exist, such as the lack of standardized protocols, unclear optimal doses, and few studies on *Ascophyllum nodosum* in *P. nigrum*. The conclusion is that combining bio-inputs with the live stake system offers a sustainable option for black pepper farming, reducing reliance on chemicals and promoting low-impact farming practices.

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RESUMO

O uso de bioinsumos tem se tornado essencial na agricultura, contribuindo para a elevação da produtividade e da qualidade do solo, para a mitigação de gases de efeito estufa e, sobretudo, para a redução dos custos de produção. Esta revisão sistemática sintetiza evidências sobre o uso de bioinsumos no cultivo da pimenta-do-reino (*Piper nigrum* L.), com ênfase no sistema de tutor vivo com *Gliricidia sepium*. Foram incluídos 14 estudos primários (1985–2025) após uma busca em cinco bases de dados científicas, seguindo as diretrizes PRISMA 2020. As evidências reunidas mostram que *Azospirillum* permitiu reduzir a adubação nitrogenada mineral em até 25% sem queda na produtividade. *Bacillus* e *Trichoderma* destacaram-se no controle de patógenos do solo, enquanto o tutor vivo com *Gliricídia sepium* reduziu os custos de implantação em cerca de 27%, mantendo o rendimento da cultura. Ainda assim, persistem lacunas importantes, como a ausência de protocolos padronizados, a definição de doses adequadas e a falta de estudos com *Ascophyllum nodosum* em *P. nigrum.* Conclui-se que a integração de bioinsumos ao sistema de tutor vivo constitui uma alternativa sustentável para a pipericultura, com potencial para reduzir a dependência de insumos químicos e consolidar práticas agrícolas de baixo impacto ambiental.

Palavras-chave: *Piper nigrum* L. Inoculante. Sistema de Tutor Vivo. Adubo Verde. Agricultura Sustentável.

RESUMEN

El uso de bioinsumos se ha vuelto esencial en la agricultura, contribuyendo al aumento de la productividad y de la calidad del suelo, a la mitigación de los gases de efecto invernadero y, sobre todo, a la reducción de los costos de producción. Esta revisión sistemática sintetiza evidencias sobre el uso de bioinsumos en el cultivo de la pimienta negra (*Piper nigrum* L.), con énfasis en el sistema de tutor vivo con *Gliricidia sepium*. Se incluyeron 14 estudios primarios (1985–2025) tras una búsqueda en cinco bases de datos científicas, siguiendo las directrices PRISMA 2020. Las evidencias recopiladas muestran que *Azospirillum* permitió reducir la fertilización nitrogenada mineral hasta en un 25% sin disminuir la productividad. *Bacillus* y *Trichoderma* se destacaron en el control de patógenos del suelo, mientras que el tutor vivo con *Gliricidia sepium* redujo los costos de implantación en aproximadamente un 27%, manteniendo el rendimiento del cultivo. Aun así, persisten importantes vacíos, como la ausencia de protocolos estandarizados, la definición de dosis adecuadas y la falta de estudios con *Ascophyllum nodosum* en *P. nigrum*. Se concluye que la integración de bioinsumos al sistema de tutor vivo constituye una alternativa sostenible para la pipericultura, con potencial para reducir la dependencia de insumos químicos y consolidar prácticas agrícolas de bajo impacto ambiental.

Palabras clave: *Piper nigrum* L. Inoculante. Sistema de Tutor Vivo. Abono Verde. Agricultura Sostenible.

1 INTRODUCTION

Black pepper (*Piper nigrum* L.) is a high-value tropical crop and is widely recognized as the most commercially important spice worldwide. Agronomically, it is a perennial species whose productivity and value addition attract both smallholder and commercial growers. Sustainable cultivation has emerged as a profitable alternative in light of rising international demand (Sreejith; Bonny, 2017). In Brazil, black pepper cultivation holds substantial economic significance in the coastal tablelands of Espírito Santo (ES), where it integrates into perennial farming systems and shapes land-use dynamics (Piassi *et al.* 2025). The state of ES reports production of 73,484 tons across 20,220 hectares under cultivation (IBGE, 2024).

The traditional intensive system relies on dead stakes (wooden posts) to support the lianas and on intensive mineral fertilization. In Espírito Santo, purchasing eucalyptus posts (1,600 units ha^{-1}, single rows at 2.5 × 2.5 m), priced at BRL 8–15 per unit, results in BRL 12,800–24,000 per hectare and accounts for approximately 60% of the field establishment cost (local supplier quotes/site visits; no published source). By adopting living stakes of gliricidia and using the average 46% cost reduction reported by Embrapa Amazônia Oriental (PA) as a benchmark, the estimated establishment cost drops from BRL 21,333–40,000 ha^{-1} (dead stakes) to BRL 11,520–21,600 ha^{-1} (living stakes) (EMBRAPA, 2025). For recurrent costs, mineral fertilization represents 10–20% of the annual budget and may be reduced by up to 30% with gliricidia due to biological N fixation and nutrient cycling (EMBRAPA, 2025). For context, Espírito Santo accounts for 60% of Brazil's production, with an average yield of 3.9 t ha^{-1} (INCAPER, 2023). Although productive, this model entails high costs, pressure on forest resources, and environmental impacts (soil degradation, nutritional imbalance, and increased incidence of phytoparasites). Additionally, the conventional model faces significant constraints such as increased soil bulk density, reduced macroporosity, and declining soil organic matter, which compromise soil health and the long-term sustainability of pepper orchards (Piassi *et al.* 2025). From a plant health standpoint, soilborne diseases, especially *Fusarium* foot rot caused by *Fusarium solani f. sp. Piperis*, can decimate entire plantations.

Accordingly, alternatives are sought to enable the crop's ecological intensification, reconciling productivity, profitability, and agronomic sustainability. In this context, the use of bioinputs in agriculture has become increasingly widespread, constituting a key approach to enhancing plant productivity while reducing the environmental impacts associated with excessive reliance on synthetic fertilizers and pesticides (Lopes *et al.* 2021). In Brazil, "bioinsumos" (bioinputs) encompass all products, methods, and technologies of predominantly biological origin that can benefit processes across the production chain and positively affect all actors integrated into the production system (BRASIL, 2020).

Currently, the National Bioinputs Catalogue, provided by Brazil's Ministry of Agriculture and Livestock (MAPA), lists hundreds of registered products for agricultural use, including microbiological agents, plant extracts, pheromones, and other naturally derived compounds. The catalogue is accessible via a mobile application or directly through the government portal, allowing users to search products by crop, intended use, and biological group (BRASIL, 2024a).

Additionally, in December 2024, Law No. 15,070 was enacted, establishing guidelines for the production, commercialization, and use of bioinputs in Brazil. The law differentiates bioinputs from pesticides and recognizes their specific characteristics within the context of national agricultural production (BRASIL, 2024b).

Within sustainable systems, bioinputs encompass several classes of products relevant to this study: (i) plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum brasilense*, capable of fixing nitrogen and synthesizing phytohormones; (ii) *Bacillus subtilis*, with biocontrol activity and growth promotion; (iii) *Trichoderma asperellum*, a biocontrol fungus that competes with phytopathogens and primes plant resistance; (iv) a seaweed-based biostimulant derived from *Ascophyllum nodosum*; and (v) a living-stake system using *Gliricidia sepium*, which replaces dead posts and provides moderate shading, nutrient cycling, and microclimatic stability.

Research on bioinputs has focused on the microorganisms and biostimulants selected for this study, applying them to crops of high agronomic relevance. Plant growth-promoting rhizobacteria (PGPR) such as *Azospirillum brasilense* show extensive evidence of efficacy in cereals and grasses (biological N fixation, auxin synthesis, enhanced rooting, and improved stress tolerance) (Hungria *et al.* 2021). Bacteria of the genus *Bacillus*, notably *B. subtilis*, combine biocontrol (antifungal lipopeptides, induced resistance) with growth promotion in legumes, vegetables, and fiber crops (Choudhary; Johri, 2009), with positive results already demonstrated for black pepper in nursery conditions (Anju *et al.* 2023). Among beneficial fungi, *Trichoderma asperellum* is a benchmark for managing soilborne diseases across multiple crops, acting through mycoparasitism, antibiosis, and induced systemic resistance (Monte; Bettiol; Hermosa, 2019).

Seaweed extracts from *Ascophyllum nodosum*, in turn, stand out as widely used biostimulants (vegetables, fruit trees, major field crops), improving growth, yield, and tolerance to drought and salinity (Goñi; Quille; O'Connell, 2018). Specifically for black pepper, early studies with microbial consortia have already shown gains in rooting and seedling vigor

(Kandiannan *et al.* 2000), which, together with the evidence above, supports the present focus on *A. brasilense, B. subtilis, T. asperellum*, and *A. nodosum* extract.

The use of *Gliricidia sepium* as a living stake adds three core mechanisms to the production system. First, nutrient cycling of nitrogen (N): as a legume, gliricidia fixes N biologically and returns N, phosphorus (P), and base cations to the system via leaves, pruning residues, and fine roots, improving the nutritional balance of the pepper canopy and reducing dependence on mineral N when pruning is conducted regularly (Moraes *et al.* 2018). Second, moderated shading and microclimate: a managed canopy dampens thermal–hydric extremes (air and soil temperature, wind speed, evaporation), reduces stress in seedlings and establishing plants, and may mitigate the severity of soilborne pathogens associated with very hot, dry microclimates (Venkatesh *et al.* 2020). Third, cost reduction and ecosystem services: replacing dead posts with service trees lowers establishment and maintenance costs and adds services (soil cover, organic matter, microbial habitat), provided pruning maintains sufficient light in the understory and avoids excessive shading (Rodrigues *et al.* 2022). In sum, when properly pruned, gliricidia reconciles physical support, nutrient cycling, and microclimatic stability, creating favorable conditions for integrating bioinputs (*Azospirillum , Bacillus, Trichoderma*) into black pepper management.

Regarding bioinputs, early studies showed that inoculation with *Azospirillum* and consortia of mycorrhizae and phosphate-solubilizing bacteria substantially improved rooting and seedling vigor in black pepper (Govindan and Chandy, 1985; Bopaiah and Khader, 1989; Kandiannan *et al.* 2000). Subsequently, *Bacillus* and *Pseudomonas* demonstrated the ability to suppress *Phytophthora capsici*, a soilborne pathogen causing foot rot, in seedlings and transplants (Ngo *et al.* 2020). Additionally, *Trichoderma harzianum* MTCC 5179 exhibited a dual role, biocontrol and biostimulation, by modulating the rhizosphere microbiota and accelerating sprouting (Syam *et al.* 2021).

Against this backdrop, this review aims to systematize the scientific knowledge available on the use of *Azospirillum brasilense, Bacillus subtilis, Trichoderma asperellum*, and a seaweed-based biofertilizer derived from *Ascophyllum nodosum* in black pepper cultivation under a living-stake system with *Gliricidia sepium*, covering all crop stages from seedling production to harvest. We seek to identify agronomic benefits, ecological impacts, and biotechnological advances, as well as to highlight research gaps to guide future scientific efforts.

2 MATERIALS AND METHODS

This systematic review followed the PRISMA 2020 guidelines (Page *et al.* 2021). The research question was structured using PICOS (Population, Intervention, Comparator, Outcomes, Study design), consistent with prior applications in agronomic studies (Machado *et al.* 2021). Definitions were as follows: Population: *Piper nigrum*; Intervention: bioinputs (*Azospirillum brasilense, Bacillus subtilis, Trichoderma asperellum, Ascophyllum nodosum*-based biofertilizers, and the living-stake system with *Gliricidia sepium*); Comparator: conventional, organic, or agroecological management; Outcomes: indicators of nutrition (foliar nutrient concentrations, associative growth), plant health (disease incidence/severity, mortality), and productivity (yield and components); Eligible study designs: experimental trials (field, nursery, greenhouse) and observational studies reporting agronomic measures.

2.1 DATA EXTRACTION, APPRAISAL, AND EXCLUSIONS

Peer-reviewed primary studies with agronomic data on *P. nigrum* that evaluated at least one target bioinput against a comparator were eligible. Exclusion criteria were: (i) ineligible species/topic (outside agronomy and/or unrelated to *P. nigrum*); (ii) absence of agronomic outcomes; (iii) reviews/syntheses or duplicates; (iv) insufficient methodology (no control or replication); and (v) missing minimum data. Reasons for full-text exclusion (n = 32) are detailed in Table 1.

Table 1

Reasons for exclusion in full-text evaluation (n = 32)

Reason	**n**
Species/topic not eligible (not *P. nigrum* or non-agronomic focus)	12
Absence of agronomic outcomes (nutrition/health/productivity)	8
Review, synthesis, or duplication	6
Insufficient methodology (no control/replication)	3
Incomplete or inaccessible data	3
Total	**32**

The reasons for exclusion are detailed in Table 1, ensuring transparency in the eligibility process. Accordingly, the final sample comprised 14 primary studies deemed consistent for qualitative synthesis.

2.2 DATA EXTRACTION AND SYNTHESIS

From each included study, we extracted: authors, year, country, experimental setting (field, nursery, greenhouse), type/arrangement of the bioinput, dose and application route, comparator, assessed outcomes, and main results. Outcomes were grouped into nutrition/growth, plant health, and productivity. Given the heterogeneity across studies (microbial species/isolates, doses, consortia, environments, assessment times, and incomplete reporting of variance), no meta-analysis was performed; instead, we conducted a narrative synthesis with thematic discussion and context-based comparison of effects.

2.3 QUALITY APPRAISAL AND ANALYTICAL LIMITATIONS

We recorded minimum methodological elements (presence of a control, replication, and management description) to support critical interpretation. Variation in study designs and the frequent absence of dispersion measures constrain quantitative extrapolation of effects. These issues are addressed in the discussion, particularly when comparing response magnitudes across environments and bioinput arrangements. The results and discussion that follow present the thematic distribution of studies, the main agronomic effects observed, and the limitations inherent to the assembled body of evidence.

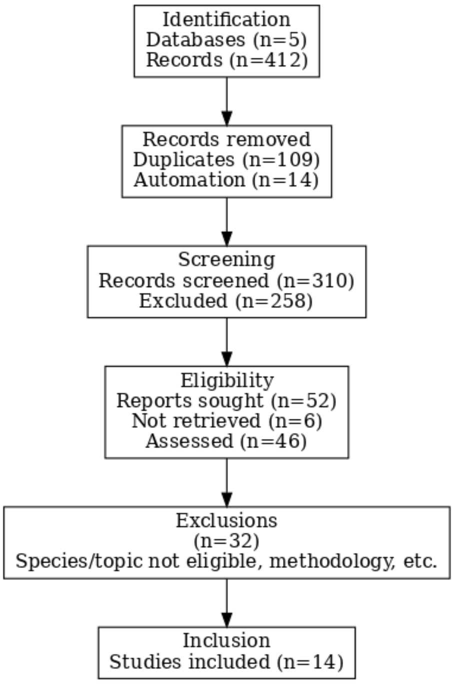
3 RESULTS AND DISCUSSION

Searches were conducted in Scopus, Web of Science, SciELO, Google Scholar, and CAB Abstracts through August 2025, with no restrictions on language or year. Strategies combined “*Piper nigrum*” or “black pepper” with intervention descriptors such as “biofertilizer,” “PGPR,” “*Trichoderma*,” “living stake,” “tutor vivo,” “gliricidia,” “*Azospirillum* ,” “*Bacillus*,” “alga,” and “*Ascophyllum*.”

A total of 433 records were identified (412 from the five databases and 21 via citation chaining). After removing 109 duplicates and 14 automated exclusions, 310 records proceeded to title/abstract screening, of which 258 were excluded. Full texts were sought for 52 studies; 6 were not retrieved. We assessed 46 full-text reports, excluding 32 for the following reasons: (i) ineligible species/topic (outside the agronomy of P. nigrum): 12; (ii) absence of agronomic outcomes: 8; (iii) reviews/syntheses or duplicate publications: 6; (iv) insufficient methodology (no control or replication): 3; and (v) minimum data unavailable: 3. Consequently, 14 studies were included in the qualitative synthesis, as depicted in the flow diagram (Figure 1).

Figure 1

PRISMA 2020 flowchart of the study selection process. Of the 433 records identified, after exclusion of duplicates (n=109) and initial screening (n=14), 310 records were evaluated. Of these, 258 were excluded in the title/abstract screening. Of the 52 full studies evaluated, 6 were not retrieved and 32 were excluded based on eligibility criteria. Ultimately, 14 studies were included in the review



Across the 14 selected studies, the literature spans roughly four decades of investigation (1985–2025). A strong geographic concentration is observed in India, which accounts for about 60% of publications, followed by Brazil, Vietnam, and Indonesia. The initial period (1980s and 1990s) was characterized by nursery trials focusing on plant growth–promoting rhizobacteria (PGPR) and mycorrhizal associations, reflecting emerging interest in reducing the use of mineral fertilizers. From the 2010s onward, the research agenda expanded to biocontrol, particularly involving Trichoderma spp. and endophytes, as well as agroecological practices such as the use of living stakes (*Gliricidia sepium* and other legumes).

The geographic concentration of research reflects the crop's production relevance: India has the largest area under black pepper but low average productivity (0.6 t ha^{-1}), which explains the large volume of local studies aimed at increasing yields (Varghese, 2024). Vietnam has established itself as the world leader in production (262,000 t yr^{-1}), with export-oriented intensive systems and documented productivity gains across multiple provinces (Clément *et al.* 2023). Indonesia, a traditional producer and a focus of management studies, ranks among the largest producers and exhibits productivity strongly modulated by environmental factors (rainfall, light, humidity), which justifies the substantial number of national publications on performance and plant health (Karmawati *et al.* 2025). In Brazil, one of the leading global producers, the latest Brazilian Institute of Geography and Statistics (IBGE) survey (2024) reported national output of 73,384 t, with an average yield of 3.6 t ha^{-1} across 20,220 hectares.

Since the 1980s, interest in bioinputs for agronomically important crops has gained traction in Brazil, driven by biological nitrogen fixation (BNF) in soybean and by Johanna Döbereiner's findings on diazotrophs associated with grasses (e.g., *Azospirillum*), as well as by a review of the national trajectory of biofertilizers that documents the selection of elite *Bradyrhizobium* strains for the Cerrado and the widespread adoption of inoculation in the 1980s–1990s, with annual savings estimated in the billions of dollars in mineral N (Bomfim *et al.* 2021). From 2010 onward, there has been an expansion toward biocontrol, motivated by declining efficacy of chemical pesticides due to resistance evolution and by regulatory/economic pressures; reviews indicate that the availability and performance of chemical controls have been constrained by stricter legislation and the rapid adaptive evolution of pests, which repositioned biopesticides (e.g., *Trichoderma, Bacillus*) as core components of Integrated Pest Management (IPM) (Lahlali *et al.* 2022).

The evolution of these themes is summarized in Table 2, which presents the frequency of each approach by historical period.

Table 2

Frequency of research topics by period

Period	PGPR/Biofertilizers	*Trichoderma*/Biocontrol	Mycorrhizae	Living tutor	Seaweed extract
≤ 2000	3	0	1	0	0
2001-2010	2	0	0	0	0
2011-2020	7	1	0	3	0
2021-2025	2	1	0	2	0
Total	14	2	1	5	0

The predominance of studies involving PGPR and biofertilizers confirms the trend toward using inoculants as a partial substitute for mineral inputs. In contrast, the few reports on mycorrhizae suggest underreporting or a secondary role for this intervention within consortia, as previously noted by Kandiannan *et al.* (2000).

Finally, the absence of records on *Ascophyllum nodosum* extracts indicates that research on black pepper remains incipient in this area, with clear potential to integrate into sustainable management practices aligned with global trends in agriculture.

3.1 NUTRITION AND GROWTH: EMPHASIS ON *AZOSPIRILLUM BRASILENSE*

The studies converge in showing that inoculation with *Azospirillum* brasilense, whether alone or combined with other bioinputs, increases plant height, biomass, and foliar N and P concentrations in seedlings. Kandiannan *et al.* (2000) demonstrated that a consortium of *Azospirillum* + phosphate-solubilizing bacteria + mycorrhizae outperformed single inoculants, producing taller seedlings with higher NPK than the control. In that nursery study, the combination of *Azospirillum* + phosphobacteria + arbuscular mycorrhiza (VAM) significantly improved the performance of black pepper cuttings: height at 6 months increased from 45.6 cm (control) to 77.0 cm, leaf area from 235.0 to 343.5 cm^2, fresh biomass from 57 to 146 g $plant^{-1}$, and dry matter from 19 to 34 g $plant^{-1}$; foliar N, P, and K also rose from 2.70, 0.13, and 1.52% to 3.27, 0.21, and 1.94%, respectively (Kandiannan *et al.* 2000). Earlier work by Govindan and Chandy (1985) and Bopaiah and Khader (1989) likewise reported enhanced rooting and vigor with *Azospirillum* in cuttings.

Similar results were obtained by Aswathy *et al.* (2018), who evaluated a microbial consortium (phosphate-solubilizing bacteria + *Azospirillum*) combined with liquid humus and fish extract. Sixty days after the second application, they recorded a 30% increase in root number, 25% in height, and 22% in leaf area relative to the control, alongside higher densities of beneficial microbes in the substrate.

At the field growth stage, Thankamani *et al.* (2011) found that *Azospirillum* inoculation allowed a 25% reduction in mineral N fertilization with no yield penalty, attributable to biological N fixation and phytohormone release. This finding is particularly relevant to the living-stake system with *Gliricidia sepium*, given that N fixation by gliricidia can be complemented by the synergistic action of *A. brasilense* at pepper roots. These results underscore the need for targeted studies on bioinputs under living-stake systems to define appropriate doses and application protocols.

3.2 PLANT HEALTH: BIOCONTROL OF *PHYTOPHTHORA CAPSICI* AND *FUSARIUM SOLANI F. SP. PIPERIS* BY *BACILLUS SUBTILIS* AND *TRICHODERMA ASPERELLUM*

Foot rot caused by *Phytophthora capsici* is the main phytosanitary constraint in India and Vietnam. In India, it causes 25–30% losses and affects 44–48% of plants, with losses reaching 1,000 t (Sreethu *et al.* 2025). In Vietnam, it is identified as the most important soilborne disease of black pepper and the leading phytosanitary problem in producing areas (Obieze *et al.* 2023). In terms of impact, >10,000 ha (≈10% of the national area) were lost in 2016 due to *P. capsici* outbreaks, with marked yield declines in hubs such as Gia Lai (Arif *et al.* 2025). In Brazil, fusariosis *(Fusarium solani f. sp. piperis*) is recognized as the principal disease of black pepper, reducing planted area by up to 32% (Ferrari *et al.* 2023), and studies in Pará corroborate *Fusarium* as the main soilborne phytopathogen associated with losses (Barata *et al.* 2021). Isolation of *Bacillus subtilis* endophytes revealed strong in vitro antagonism against the pathogen in plate assays, with a significant reduction in seedling mortality in nurseries (Aravind *et al.* 2009). Ngo *et al.* (2020) selected *Bacillus* isolates (*B. siamensis, B. velezensis*, and *B. methylotrophicus*), and inoculation led to lower incidence of rotten roots (≤11%) and high seedling survival. In nursery settings, bacterization with endospore-forming *Bacillus* strains (*B. subtilis, B. velezensis, B. pumilus*) promoted seedling growth and suppressed foot rot caused by *P. capsici* in black pepper; treated seedlings exhibited greater numbers of roots, shoots, and leaves, and drastically reduced disease severity relative to the control (Anju *et al.* 2023).

The fungus *Trichoderma asperellum* exhibited a dual role—biocontrol and biostimulation—by modulating the soil microbial community (Umadevi *et al.* 2018) and, in nurseries, advancing sprouting and increasing both leaf number and shoot length when combined with foliar fertilization (Syam *et al.* 2021).

Eapen *et al.* (2009) conducted a multi-year trial comparing different biological agents with chemical treatments in an infested field. Consolidated data across four harvests are presented in Table 3.

Table 3

Incidence of diseased plants and average productivity of black pepper after four years of biological and chemical treatments. Prepared by the author (2025) based on Eapen et al (2009)

Treatment	Diseased plants (%)	Productivity (kg plant^{-1})
Control	32,4	1,02
Trichoderma harzianum	36,9	1,32
Pochonia chlamydosporia	20,5	1,83
Pasteuria penetrans	22,8	1,18
Nematicide + phosphonate	34,4	1,50
Isolated nematicide	15,3	1,35

Source: Prepared by the author (2025) based on Eapen et al (2009).

The association with *P. chlamydosporia* delivered the highest yield, outperforming even the chemical management regime, whereas the standalone nematicide achieved the lowest disease incidence but only intermediate productivity. These findings reinforce the potential of bioinputs to couple pathogen suppression with increased production, particularly when integrated with organic soil management and the living-stake system.

3.3 PRODUCTIVITY AND FIELD PERFORMANCE: INTEGRATING BIOINPUTS WITH THE *GLIRICIDIA SEPIUM* LIVING-STAKE SYSTEM

Yield gains and economic sustainability become evident when bioinputs are continuously incorporated into management under a living-stake system. Thankamani *et al.* (2011) showed that PGPR integrated with fertilization (50% N + Mg) achieved a productivity peak, with a maximum yield of 2,207 g plant^{-1}, surpassing standalone NPK (1,950 g plant^{-1}); on average across treatments, inoculation increased production from 790 to 1,461 g plant^{-1} (+85%) and raised soil N, K, and Mg.

In the living-stake system with *Gliricidia sepium*, studies indicate that peppers supported by this tree species deliver yields equivalent to or greater than systems using dead stakes, while reducing establishment costs and generating environmental co-benefits. An impact assessment in Pará reported an ≈27% reduction in establishment cost per hectare when replacing wooden posts with gliricidia, alongside positive socio-environmental performance and adoption still <1% of the state's planted area, highlighting the need for technological diffusion (Moraes *et al.* 2018). Rodrigues *et al.* (2022) likewise showed that the G. sepium living stake lowers initial costs by 27% and promotes microclimatic stability and nutrient cycling.

Venkatesh *et al.* (2020) emphasized that the choice of support species is critical: grevillea and agarwood allow greater light transmission and favor early pepper growth, whereas *G. sepium* requires rigorous pruning to avoid excessive shading. Nonetheless, when properly managed, *G. sepium* offers significant advantages, including biological nitrogen fixation, which can potentiate the action of *Azospirillum brasilense* applied to pepper roots.

The cumulative nutritional and plant-health benefits provided by bioinputs carry over into the reproductive phase. Parvathi and Waibel (2015) reported that, from the third year onward, organic systems based on composting and microbial inoculants out-yielded conventional systems by 12% on Indian farms, attributing the gain to lower plant mortality and sustained nutritional balance.

3.4 SYNTHESIS OF AGRONOMIC STUDIES

This review demonstrates that bioinputs have the potential to transform black pepper management under a living-stake system with *Gliricidia sepium*. *Azospirillum brasilense*, in combination with other bioinputs, improves rooting, nutrient uptake, and vegetative vigor, enabling partial reductions in nitrogen fertilization without yield penalties, in fact, with productivity gains (Kandiannan *et al.* 2000; Thankamani *et al.* 2011). Inoculation with *Bacillus subtilis* and application of *Trichoderma asperellum* are effective in suppressing Phytophthora capsici, prolonging orchard lifespan and reducing losses (Aravind *et al.* 2009; Ngo *et al.* 2020; Umadevi *et al.* 2018).

The living-stake system with *Gliricidia sepium* stands out as an agroforestry strategy that maintains yield, reduces costs, and promotes nutrient cycling and moderated shading, provided that the tree species is well chosen and pruning is properly managed (Moraes *et al.* 2018; Venkatesh *et al.* 2020; Rodrigues *et al.* 2022). Integration between *G. sepium* and bioinputs applied to pepper vines can generate synergistic effects, particularly for biological nitrogen fixation and disease control.

Relevant gaps nonetheless remain: (i) the absence of multi-season trials to assess cumulative bioinput effects in perennial systems; (ii) standardization of formulations, doses, and inoculation protocols tailored to the G. sepium living-stake system; (iii) detailed economic analyses linking inoculant costs, fertilizer savings, and yield returns; (iv) evaluation of inoculant compatibility with commonly used pesticides; and (v) experimentation with *Ascophyllum nodosum* extract in *P. nigrum*, which is lacking in the current literature. Therefore, future studies should include long-term trials, address edaphoclimatic variability, and integrate economic and plant-health analyses to consolidate the use of bioinputs in the living-stake system. The main studies identified in this review are summarized in Table 4 below.

Table 4

Agronomic studies on bioinputs in Piper nigrum

Study (year)	Country	Bioinput (type/arrangement)	Environment	Main summary findings
Govindan; Chandy, 1985	India	*Azospirillum*	Nursery	Inoculation increases rooting and cutting vigor.
Bopaiah; Khader, 1989	India	*Azospirillum* + Azotobacter	Nursery	Taller seedlings with higher NPK levels.
Kandiannan *et al.*2000	India	*Azospirillum* + phosphobacteria + mycorrhizae	Nursery	Intercropping produces more vigorous seedlings than isolated seedlings.
Thankamani *et al.*2011	India	*Azospirillum* + 50% N + Mg	Field	Higher yield; improved soil N, K, and Mg, and leaf N and Ca levels.
Aravind *et al.*2009	India	Pseudomonas and *Bacillus* endophytes	Nursery	Antagonism to Phytophthora and reduction of seedling rot.
Eapen et al, 2009	India	Endophyte consortium	Nursery	Improved survival and control of Meloidogyne spp.
Ngo *et al.*2020	Vietnam	*Bacillus* (diversos isolados)	Nursery	Root rot ≤ 11%; high seedling survival.
Umadevi *et al.*2018	India	*Trichoderma harzianum* MTCC 5179	Field	Positively modulates microbiota and improves health.
Syam et al, 2021	Indonesia	*Trichoderma* + foliar fertilization	Nursery	Early sprouting, increased leaf and shoot length.
Aswathy *et al.*2018	India	PGPR + organics (fish extract, humic acid)	Nursery	Integrated "package" outperformed isolates in growth and rooting.

Study (year)	Country	Bioinput (type/arrangement)	Environment	Main summary findings
Silva *et al.*2024	Brazil	Amazonian endophytes (PGPR)	Lab./nursery	Native isolates present ACC deaminase, P solubilization, and nifH genes.
Venkatesh *et al.*2020	India	Living guardians (grevillea, agarwood, gliricidia, etc.)	Field	Grevillea/agarwood > gliricidia in growth; pruning management is crucial.
Moraes *et al.*2018	Brazil	Living guardian (gliricidia)	Field	Reduced implementation costs; microclimatic stability.
Rodrigues *et al.*2022	Brazil	Live tutor (various)	Field	Tutor type influences growth and production components; management determines success.

As shown in Table 4, the literature ranges from pioneering contributions on plant growth–promoting rhizobacteria to recent studies on biocontrol strategies and living-stake systems. More than reiterating previously reported results, the body of work highlights the diversity of methodological approaches and experimental contexts, underscoring the need for integrated interpretations. This synthesis makes it possible to identify consolidated trends and critical gaps, which will be explored in the following discussion, with emphasis on the different groups of bioinputs and their interaction with the black pepper production system.

Although no studies have reported the use of *Ascophyllum nodosum* specifically in black pepper, recent literature indicates that its extracts act positively in other crops, improving germination, growth, yield, and tolerance to abiotic stresses, including salinity (Kumari *et al.* 2023; Shukla *et al.* 2019). These findings suggest clear potential for future trials to be conducted in *P. nigrum*.

4 CONCLUSION

This PRISMA 2020, guided systematic review shows that the strategic use of bioinputs (*Azospirillum brasilense*, *Bacillus subtilis*, *Trichoderma asperellum*, and an *Ascophyllum nodosum*–based biofertilizer), together with the *Gliricidia sepium* living-stake system, provides a pathway for ecological intensification of black pepper cultivation. In combination, these elements improve mineral nutrition, strengthen plant-health resilience, and enhance production sustainability, enabling partial reductions in chemical inputs and decreasing dependence on wooden posts.

The compiled evidence demonstrates consistent benefits of bioinputs for black pepper. In the field, inoculants such as *Azospirillum brasilense* allowed reductions in mineral fertilization without yield penalties, while biocontrol agents, particularly *Bacillus subtilis* and *Trichoderma asperellum*, suppressed root diseases and increased productivity. From the third year onward, organic systems based on composting and microbial bioinputs outperformed conventional management in yield and showed potential to improve the phytochemical quality of peppercorns.

To fully realize these benefits, it is essential to develop and disseminate standardized protocols for applying bioinputs within the *Gliricidia sepium* living-stake system, accounting for Brazil's diverse edaphoclimatic conditions. Such standardization would ensure greater reproducibility, efficiency, and safety in the use of these technologies, facilitating adoption by both smallholders and large-scale producers.

Among the research priorities identified, a key need is to monitor the persistence of beneficial microorganisms in the rhizosphere after transplanting and to relate this persistence to productivity over multiple crop cycles. It is likewise essential to establish standardized doses and protocols for inoculant consortia, again considering Brazil's edaphoclimatic diversity. In parallel, quantifying piperine and essential-oil contents and assessing the sensory attributes of peppercorns produced with bioinputs are crucial to substantiate demonstrable quality gains.

From an economic standpoint, there is a concrete opportunity for commercial black pepper nurseries to integrate bioinputs at the seedling stage, supported by a favorable regulatory environment, the National Bioinputs Program, the National Bioinputs Catalogue, and the strong growth of Brazil's biologicals market. The size of this market underscores the importance of scientific validation: in the 2023/24 season, Brazil's biopesticides segment reached approximately BRL 3.7 billion, with steady expansion over the last three seasons (FGV/CROPLIFE BRASIL, 2024), indicating real demand for biological solutions with proven efficacy and standardized protocols for use in black pepper.

In this context, recent nursery results already show significant agronomic gains with endospore-forming Bacillus, including higher seedling vigor and effective suppression of foot rot, reinforcing the relevance of validation trials under commercial conditions (Anju *et al.* 2023).

Therefore, the importance of future investigations is consolidated, advancing from controlled nursery experiments to field validations and addressing interactions among different bioinputs (*Azospirillum brasilense*, *Bacillus subtilis*, *Trichoderma asperellum*, *Ascophyllum nodosum* extracts) and the *Gliricidia sepium* living-stake system. Such studies should aim not only to confirm agronomic efficacy but also to demonstrate economic feasibility, adaptability across edaphoclimatic gradients, and impacts on final product quality, factors that are fundamental for large-scale adoption of these sustainable practices in Brazilian black pepper production.

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