JUATIKA
JURNAL AGRONOMI TANAMAN TROPIKA
VOL. 8 No. 2 May 2026

DOI :https://doi.org/10.36378/juatika.v8i2.5069
eissn 2656-1727
pissn 2684-785X
pages : 548 – 559

REVIEW ARTICLE Open Access

Biological Control of Leaf Diseases Caused by *Pestalotiopsis sp.*: A Bibliometric and Narrative Review

Anita Setyawati[1], Yossi Aprian Nursalim[1,*], Saripudin[2], Daniel Saputra[1]

Abstract

Pestalotiopsis sp. is an important fungal pathogen associated with leaf diseases, which pose a significant threat to sustainable crop production. This study aims to identify publication trends, global research distribution, and key research focuses related to the biological control of *Pestalotiopsis* spp. in plants. Data were collected from scientific publications indexed in the Scopus database from 2005 to 2025. Using AND/OR search terms, namely: (Title-Abs-Key (Biological And Control) And Title-Abs-Key (*Pestalotiopsis*)) And Pubyear > 2004 And Pubyear < 2026 And (Limit-To (Subjarea, "Agri") Or Limit-To (Subjarea, "Bioc") Or Limit-To (Subjarea, "Medi") Or Limit-To (Subjarea, "Envi") Or Limit-To (Subjarea, "Immu")) And (Limit-To (Doctype, "Ar")) And (Limit-To (Language, "English")), a total of 91 scientific articles were identified. The selected publications were analyzed using VOSviewer version 1.6.20 to evaluate publication trends, collaboration networks, and thematic evolution. The results show a significant increase in research activity, particularly after 2021, with a shift towards mechanism-based biological control strategies. Key antagonistic microorganisms, including *Trichoderma*, *Bacillus*, *Pseudomonas*, and endophytic fungi, exhibit strong inhibitory effects through antibiosis, enzymatic degradation, competition, and induction of plant resistance. A key strength of this review is the integration of bibliometric mapping with mechanistic synthesis, which allows for the identification of thematic evolution, key biocontrol agents, and critical research gaps. Although biological control has demonstrated strong effectiveness under laboratory conditions, field validation and large-scale implementation are still limited. This review provides a comprehensive scientific reference and practical guidance to support future research and accelerate sustainable biological control strategies for *Pestalotiopsis*-associated diseases.

Keywords: *Bacillus subtilis* subsp. *spizizenii*, *Bacillus velezensis*, *Fusarium*, *Pseudomonas silvicola*, *Trichoderma*

1. Introduction

Pestalotiopsis spp. is a plant pathogenic fungus that attacks various economically important plant species. This pathogen is necrotrophic, causing symptoms such as spots, wilting and leaf fall, as well as stem base rot, which results in significant crop yield losses. Several plants have been reported to be susceptible to *Pestalotiopsis* infection, including tea (*Camellia sinensis*), oil palm (*Elaeis guineensis*), guarana (*Paullinia cupana*), rubber (*Hevea brasiliensis*), strawberry (*Fragaria × ananassa*), stone pine (*Pinus pinea*) (Alchemi & Jamin, 2022; Escalante et al., 2010; Gualberto et al., 2021; Martínez & Plata-Rueda, 2013; Pandey et al., 2024) (Alchemi & Jamin, 2022; Escalante et al., 2010; Gualberto et al., 2021; Martínez & Plata-Rueda, 2013; Pandey et al., 2024).

Symptoms of *Pestalotiopsis* infection vary depending on the host plant and environmental conditions. In hazelnuts, wilting and leaf spots are characterised by yellowing and leaf necrosis (Vasić et al., 2017). In guava (*Psidium guajava*), infection causes light brown lesions surrounded by dark brown borders on the leaves, as well as prominent, corky, necrotic lesions on the fruit exocarp (Keith & Zee, 2010). Cardamom shows symptoms of rectangular spots parallel to the leaf veins, initially appearing on young and soft leaves (Gopi et al., 2018). In blueberry plants, leaf spots are characterised by dark

*Correspondence: nursalimyossi@gmail.com
1) Universitas Sriwijaya - Jl. Palembang-Prabumulih, KM 32, Inderalaya, Kabupaten Ogan Ilir, Sumatera Selatan 30662, Indonesia
2) Balai Karantina Hewan, Ikan, dan Tumbuhan Sumatera Selatan - Jl. Taman Sari, Kec. Alang-Alang Lebar, Kota Palembang, Sumatera Selatan 30961, Indonesia

lesions (Araujo et al., 2023). Oil palms show damage to the leaves, causing the fronds to fall off (Escalante et al., 2010; Martínez & Plata-Rueda, 2013). Spots and fruit rot on grapevines cause post–harvest fruit rot (Jayawardena et al., 2015). Branch blight: bayberry branch blight causes severe damage to plants (Ren et al., 2013). Stems and roots show symptoms of Ericaceae plants, with yellowing of leaves, stems, and roots, and black or dark green aservuli on diseased tissue (McQuilken & Hopkins, 2004). In yew trees, there is an increase in the production of superoxide anion radicals and hydrogen peroxide in the leaves, indicating oxidative stress (Rybus-Zając, 2005).

The *Pestalotiopsis* pathogen causes significant damage and economic losses to various crops, particularly oil palm and tea plants. In Ghana, leaf spot outbreaks caused by *Pestalotiopsis* sp. on oil palm seedlings reached an incidence rate of 85%, indicating an epidemic situation (Lekete et al., 2019). In Venezuela, *Pestalotiopsis*, along with *Curvularia*, caused severe yield losses in oil palm plantations (Escalante et al., 2010). In Colombia, damage caused by *Pestalotiopsis* was exacerbated by the leaf-dropping Lepidoptera larvae and significant damage to the leaves of E. guineensis (Martínez & Plata-Rueda, 2013). To address the problem of *Pestalotiopsis* infection in various crops, several control methods have been developed. These methods can be broadly categorized as biological, chemical, and cultural practices. Control measures: Biological control involves the use of natural organisms to suppress *Pestalotiopsis* infection. This method is environmentally friendly and sustainable, as various microbes, including fungi and bacteria, can act as biological control agents. *Trichoderma asperellum* and *Streptomyces* sp. have demonstrated antagonistic activity against plant pathogens (Karamova et al., 2019). Furthermore, endophytic microorganisms can protect host plants by releasing metabolites that inhibit pathogen growth (Kumar et al., 2023). Mycoviruses such as *Pestalotiopsis* theae chrysovirus-1 can transform pathogenic fungi into non-pathogenic endophytes, reducing their virulence and conferring resistance to host plants (Zhou et al., 2021). Chemical control involves the use of fungicides and other chemicals to control *Pestalotiopsis* infections. A five-spray program alternating prochloraz and carbendazim has been effective in reducing the incidence and severity of the disease in ericaceous plants (McQuilken & Hopkins, 2004). However, continuous use of chemical pesticides can cause environmental pollution, pathogen resistance, and decreased soil fertility (Chandoliya et al., 2023; Kumar et al., 2023)

Cultivation practices involve modifying the growing environment to reduce the incidence of *Pestalotiopsis* infection. Subsurface irrigation has been shown to be more effective than overhead watering in reducing disease incidence (McQuilken & Hopkins, 2004). Disinfecting pots and floors with hydrogen peroxide/peracetic acid can significantly reduce disease severity when combined with fungicide treatments. Crop rotation and intercropping: These practices disrupt the pathogen life cycle and improve soil health, thus contributing to pathogen control (Cucu et al., 2025). Maintaining biodiversity: Encouraging biodiversity in agricultural systems can help manage pathogen populations and increase plant resilience (Cucu et al., 2025).

Although research on *Pestalotiopsis* continues to grow, previous review studies still have limitations. Previous studies on diseases and pests in rubber plants primarily analyzed global research trends, scientific collaborations, and general research themes related to various pathogens. These studies focused solely on various pests and diseases caused by *Pestalotiopsis* spp. Furthermore, these studies relied solely on bibliometric analysis and did not provide a narrative synthesis of biological control mechanisms, ecological interactions, or practical applications of biological control agents (Chen et al., 2023). The fungal pathogen *NeoPestalotiopsis* spp. is a major cause of various diseases in strawberries, including leaf spot, fruit rot, basal stem rot, and root rot, with a primary emphasis on the biology and epidemiology of the pathogen, such as its life cycle, infection mechanisms, and disease spread patterns in strawberry production systems (Ávila-hernández et al., 2025).

In contrast, this review specifically focuses on the biological control of leaf diseases caused by *Pestalotiopsis* spp., integrating bibliometric analysis with a comprehensive narrative review. This approach allows for a deeper understanding of research trends while synthesizing current knowledge on antagonistic microorganisms, pathogen suppression mechanisms, and their potential applications in sustainable disease management. By combining quantitative bibliometric mapping with qualitative biological interpretation, this review provides a more focused and mechanistic perspective that has not been addressed in previous bibliometric studies. Based on this background, this study aims to map two decades of research on *Pestalotiopsis* biological control from 2005 to 2025 using a bibliometric analysis of Scopus–indexed publications enriched with narrative analysis. This study seeks to answer the following research questions: 1)What are the publication trends and developments in *Pestalotiopsis* sp. biological control research during the 2005-2025 study period 2) What is the main focus of *Pestalotiopsis* sp., and what are the future directions of *Pestalotiopsis* sp. biological control research (future research) based on the bibliometric results and narrative review? 3) Who are the authors, institutions, and countries that have contributed most to the research 4) What are the most frequently occurring topics and how are they related based on keyword co-occurrence analysis. The results of this study are expected to provide a comprehensive overview of the development of *Pestalotiopsis* sp. Research on biological control of *Pestalotiopsis* sp., highlights leading authors and institutions, and provides a scientific basis for research and policy planning that supports ecosystem resilience and sustainable rubber production through biological control innovations.

2. Material and Methods

This study was designed using a bibliometric approach combined with a narrative review to map the global development of research on the biological control of *Pestalotiopsis* in rubber agricultural ecosystems over the past two decades (2005–2025). The study includes scientific publications from all countries indexed in the Scopus database, ensuring a comprehensive global representation of research activity in this field. A bibliometric approach was used to measure scientific productivity, analyze collaborative networks across countries, institutions, and authors, visualize relationships between documents, and identify the structure and evolution of the knowledge domain. Furthermore, bibliometric findings were interpreted through a narrative synthesis to elucidate research trends, key themes, biological control mechanisms, and emerging research directions. The integration of bibliometric mapping and narrative analysis provides a comprehensive global perspective on the development, knowledge structure, and future directions of biological control research targeting *Pestalotiopsis* in agricultural ecosystems.

All data used were based on Scopus data with search techniques developed and following PRISMA guidelines which are mandatory reporting elements for systematic reviews and meta-analyses (Liberati et al., 2009). The data search process was conducted on December, 2025 using a combination of keywords developed based on standard terminology in biocontrol research and coffee agroecosystems. The keywords used included AND/OR, namely: (TITLE-ABS-KEY (biological AND control) AND TITLE-ABS-KEY (*Pestalotiopsis*)) AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA, “AGRI”) OR LIMIT-TO (SUBJAREA, “BIOC”) OR LIMIT-TO (SUBJAREA, “MEDI”) OR LIMIT-TO (SUBJAREA, “ENVI”) OR LIMIT-TO (SUBJAREA, “IMMU”)) AND (LIMIT-TO (DOCTYPE, ‘ar’)) AND (LIMIT-TO (LANGUAGE, “English”)). The initial execution of the search query applied to the title, abstract, author keywords, and author keywords plus fields in the Scopus database resulted in 91 documents. In the first screening, publications were limited to the years 2000-2025. Documents were limited to relevant subject areas in the field of Agricultural and Biological Sciences resulting in 50 articles. Only original papers were selected, amounting to 47 articles. To ensure language consistency and facilitate bibliometric analysis, further selection was carried out by limiting articles to only 39 articles in English, and at this stage the number of documents that met the final criteria was determined (Figure 1).

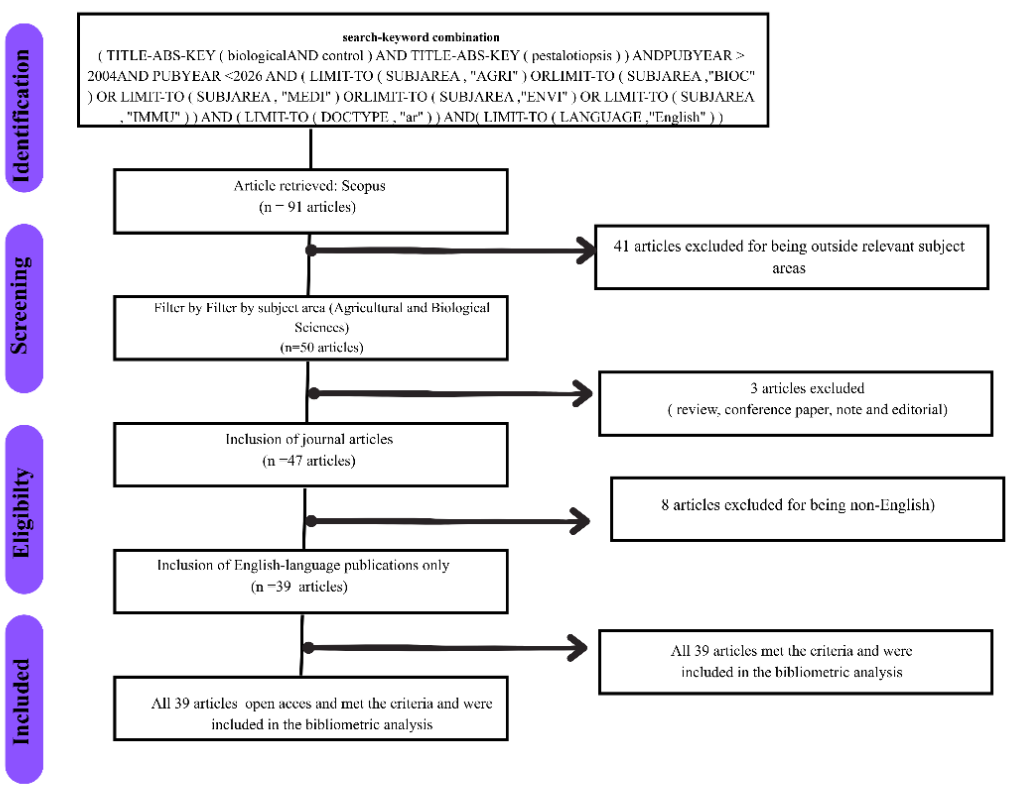

Figure 1. Research flowchart

All documents were screened through title and abstract review to ensure their relevance to the topic of biological control in plants. This stepwise procedure was undertaken to maintain the validity of the dataset and ensure that the included articles were truly representative of the research landscape to be mapped. These 39 articles were then used as the basis for the bibliometric analysis and narrative review in this study. The search method and article selection procedure are shown in Table 1. The development of scientific advances in the field of biological control of *Pestalotiopsis* sp. leaf disease, the geographic distribution of contributing countries related to *Pestalotiopsis* sp. in crop, and the main research focus based on the co-occurrence of keywords in the biological control of *Pestalotiopsis* sp. in crop were analyzed using VOSviewer software (version 1.6.20) to construct and visualize a bibliometric network map.

Table 1. Search strategies for obtaining data from the intended literature sources

String of search terms	(TITLE-ABS-KEY (biological AND control) AND TITLE-ABS-KEY (*Pestalotiopsis*)) AND PUBYEAR > 2004 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "BIOC") OR LIMIT-TO (SUBJAREA , "MEDI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "IMMU")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))
looked in	Topic: title, abstract, author keywords, and keywords plus
Database	Scopus
The most recent update	December , 2025
Initial Result	91 articles
Criteria for inclusion	Agricultural and Biological Sciences Environmental Science Biochemistry, Genetics and Molecular Biology Immunology and Microbiology Medicine Article English
Stage of screening	52 articles were removed
Last sample	39 articles

Next, the identification of the most relevant sources, analysis of the most popular author keywords (Table 2), and evaluation of the evolution of research in *Pestalotiopsis* sp. control were performed using R software (version 4.5.2) through the Bibliometrix package and its web interface, Biblioshiny. These tools were applied to generate source impact metrics, keyword frequency distributions, and analysis of thematic evolution over time.

3. Results and Discussion

3.1. The development of scientific progress in the field of biological control of *Pestalotiopsis* sp. leaf diseases

Figure 2 showed that publications on the biological control of *Pestalotiopsis* sp. for leaf diseases during the period 2005–2025 showed an overall increasing trend with variations between years. In the initial phase (2005–2011), the number of publications was relatively low and inconsistent. Starting in 2012, a gradual increase occurred that continued until 2017, followed by an acceleration in publications in the period 2018–2020. The peak of publications was reached in 2021–2023, reflecting an increased research focus on sustainable biological control strategies. Despite a temporary decline in 2024, a surge in 2025 confirms the relevance and sustainability of this topic in rubber leaf fall research.

Table 2 illustrates the distribution of the most influential publication sources in research related to *Pestalotiopsis* sp., particularly in the context of microbiology, plant pathology, and biological control. The dominance of Frontiers in Microbiology (7 articles) confirms that the field places a strong emphasis on microbiological and molecular fundamentals, including the exploration of antagonistic microorganisms, microbe-pathogen interactions, and omics approaches as a basis for developing biological control strategies. The presence of Biological Control (5 articles) as the second most productive source indicates that *Pestalotiopsis* is consistently positioned as a plant pathogen, not a pest, and that the preferred approach is biological disease control. This reinforces the argument that the research focus has shifted from simply eliminating pathogens to evaluating antagonistic agents and the effectiveness of biologically based control. Journals such as the International Journal of

Molecular Sciences, the Journal of Applied Microbiology, and the Journal of Fungi (3 articles each) reflect mechanistic insights through molecular and physiological studies of the fungus, as well as testing applications of antagonistic microbes. This distribution suggests that research is not stopping at the descriptive level, but rather moving towards understanding the biological and molecular processes underlying antifungal activity. Sources with fewer articles but strong themes, such as Australasian Plant Pathology and Fungal Biology, show specific contributions to plant pathology and fungal biology, while the emergence of Marine Drugs shows a cross-disciplinary expansion into the exploration of bioactive metabolites, although its contribution is still limited and has not yet become mainstream in plant disease management.

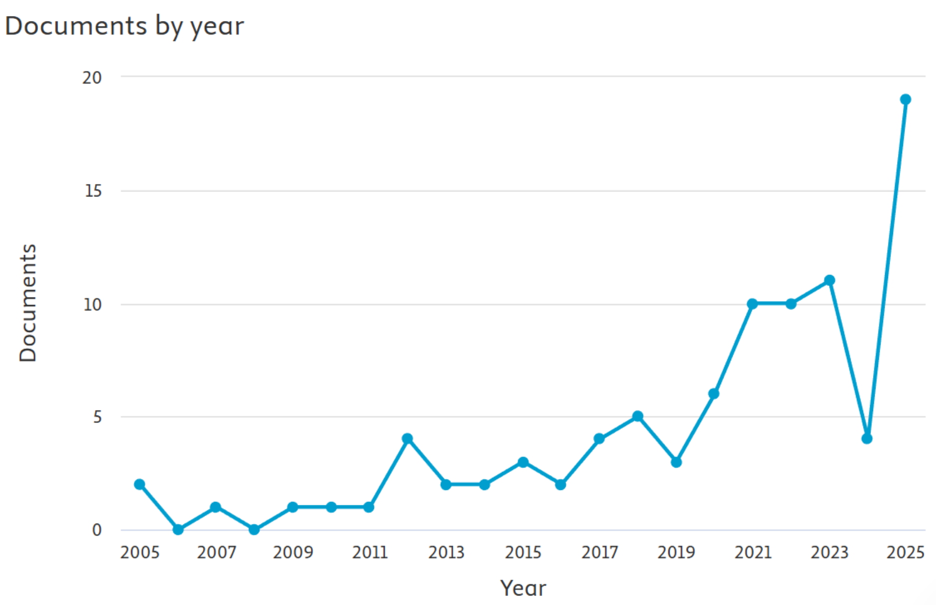

Figure 2. Distribution of publications by year

Tabel 2. Most relevan source

Sources	Articles
Frontiers In Microbiology	7
Biological Control	5
International Journal Of Molecular Sciences	3
Journal Of Applied Microbiology	3
Journal Of Fungi	3
Australasian Plant Pathology	2
Biocontrol	2
Fungal Biology	2
Marine Drugs	2
Microbiological Research	2

3.2. Geographical distribution of contributing countries related to biological control and *Pestalotiopsis* sp. leaf diseases

Figure 3 showed the geographical distribution of publications related to *Pestalotiopsis* sp. in rubber as well as the countries with the largest contribution to coffee pest biological control research. China occupies the dominant position with more than 30 publications, reflecting its strong research capacity and the intensity of disease issues in rubber and coffee plantations in the country. Brazil and India follow as the next major contributors with a significant number of publications, in line with their position as major producers of tropical plantation commodities. The United States and Mexico also show a prominent research role, despite not being major rubber producers, but are active in biocontrol and agricultural microbiology research. The UK, Poland and Spain make moderate contributions, mainly through laboratory studies and international collaborations. Meanwhile, Egypt and Indonesia are at a lower publication level, suggesting that local research on *Pestalotiopsis* sp. and its control still needs to be improved despite the large plantation potential of both countries. Overall, this pattern illustrates that most research comes from countries with high research capacity or countries with significant disease pressure on rubber commodities.

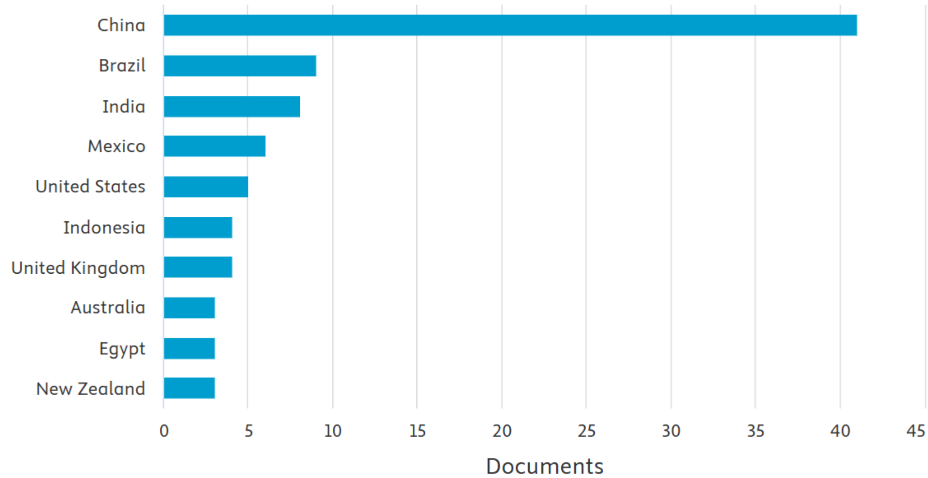

Figure 3. Top ten countries with the most publications on biological control of *Pestalotiopsis* sp.

3.3. Main research focus (keywords) in biological control of *Pestalotiopsis* sp leaf disease

Figure 4a displays a keyword co-occurrence network depicting the intellectual structure and dynamics of biological control research on *Pestalotiopsis*, a plant fungal pathogen. Overall, the network exhibits a dense and interconnected pattern, indicating that this field of research has developed conceptually, but remains concentrated on laboratory and mechanistic approaches. The center of the network is dominated by *Pestalotiopsis* and articles, which are strongly linked to phylogeny, antifungal activity, and biological control. This configuration highlights the pathogen-centric nature of research, with a primary focus on taxonomic identity, phylogenetic relationships, and evaluation of antagonistic ability, rather than agroecosystem-based approaches or integrated disease management. The strong linkage between *Pestalotiopsis* and phylogeny reflects the importance of molecular approaches in resolving species complexes, which remain fundamental to the development of biological control strategies. The red cluster represents the functional axis focusing on antifungal activity, bacterial strain, soil microflora, plant growth, and key species such as *Bacillus velezensis*. This cluster indicates a shift in research toward characterizing pathogen inhibition mechanisms, including metabolite production and effects on plant growth. However, the strong associations within this cluster are not matched by significant connections to terms such as field application, formulation, or environmental stability, indicating that most findings are still at the in vitro or controlled conditions testing stage. The green cluster highlights the biological foundation of the research, characterized by keywords such as endophyte, microbiology, genetics, and fungus. The close association with other pathogens such as Fusarium, Colletotrichum, and Phoma suggests a tendency to generalize the potential of biocontrol agents across pathogen systems. While this approach broadens mechanistic understanding, the weak linkage to implementation strategies suggests that knowledge transfer from the biological level to practical disease management remains limited. The blue cluster reflects a cross-disciplinary expansion that includes chemistry, metabolism, ascomycetes, and non-agricultural terms such as animal cell and human. This demonstrates increased interest in metabolite characterization and toxicity testing, but also indicates a potential shift in focus that could reduce direct relevance to plant disease control if not strategically integrated within an agricultural context.

Figure 4b is an overlay visualization of the keyword co-occurrence network showing the temporal dynamics of the research theme of biological control of *Pestalotiopsis* sp. The colors represent the average year of keyword appearance, from blue-purple (older themes) to green-yellow (newer themes), thus understanding the chronological direction of research evolution. In the initial spectrum (blue-purple, ±2018–2019), research was dominated by fundamental keywords such as fungi, fungi, fungal isolation, and nucleotide sequences. This indicates that the initial research phase focused largely on pathogen identification, microbial exploration, microbiological isolation and characterization, endophytes, initial classification, and taxonomic positioning of *Pestalotiopsis* and related fungi. There is no need to worry about the content and text within the text. Entering the transition phase (bluish-green, ±2020–2021), keywords such as biological control, biocontrol agents, in vitro studies, phylogeny, and antifungal agents began to occupy a central position. This reflects a shift from biological exploration to functional evaluation, specifically testing antagonism and agent potency under controlled biological conditions. *Pestalotiopsis* remains the core node, confirming that the evolution of the theme is to strengthen the focus, not to change the research objectives.

This period extends further (late in the year, between 2022 and 2024), and also poses risks to antifungal activity, *Bacillus velezensis*, plant growth, soil microflora, metabolism, and human and other animal cells. However, users have the right to choose different methods of use, which can be used in different ways, which can be used to protect people worldwide. However, the emergence of this interdisciplinary term also indicates the potential for broadening the research focus, which is not yet fully integrated with the needs of plant disease management in the field.

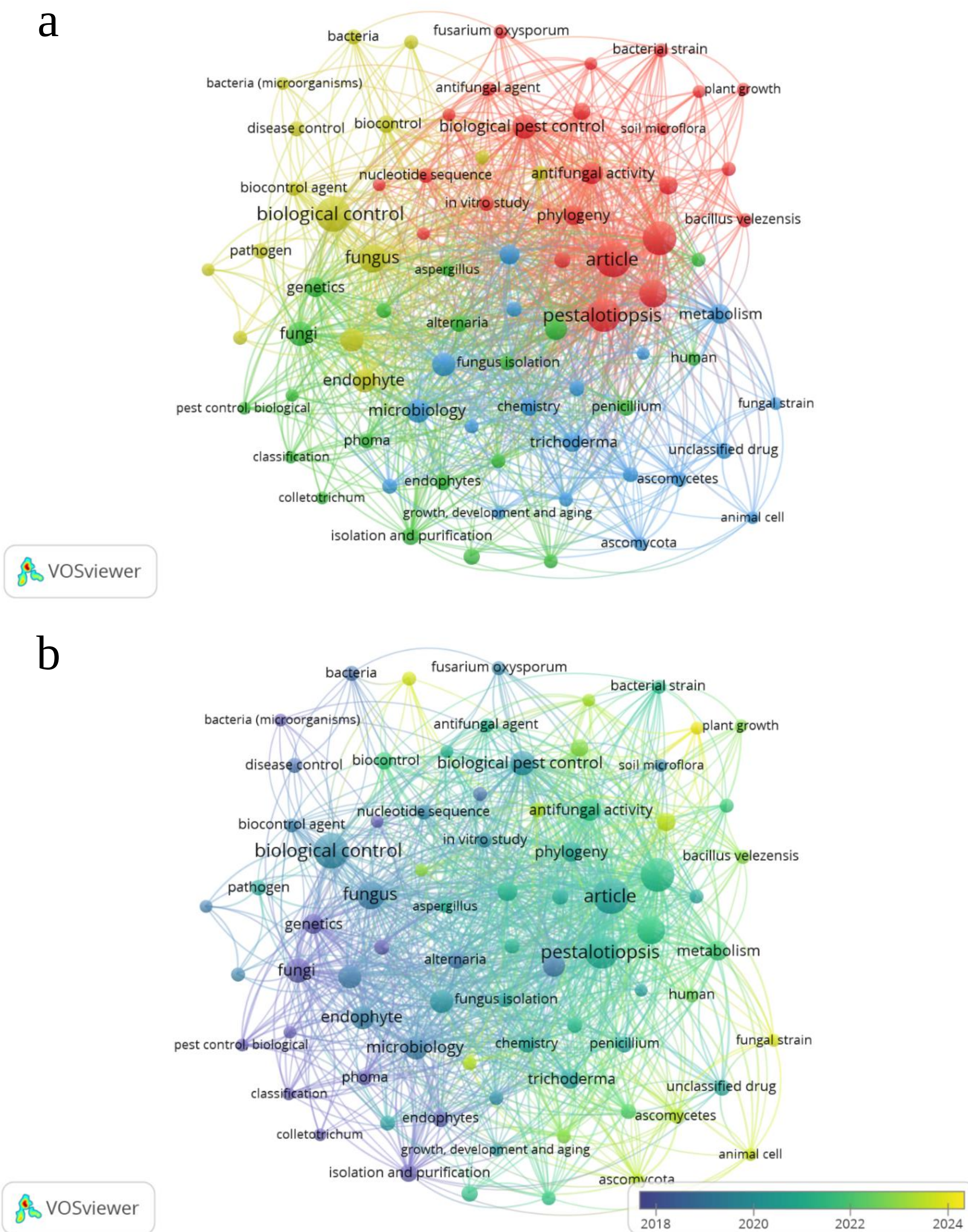

Figure 4. The association between the author's keyword occurrence related to *Pestalotiopsis* biological control a. network visualization b. overlay visualization

Tabel 3. The most popular keywords by author

Keyword	Occurrences	Total link strength
Pestalotiopsis	33	470
controlled study	22	344
Fungus	22	328
biological pest control	18	282
Microbiology	16	274
plant disease	16	263
Fungi	18	240
Fusarium	14	227
Endophyte	16	225
plant diseases	15	225
genetics	12	212
antifungal activity	14	208
biological control agent	12	208
phylogeny	12	205

Table 3 highlights a mature but methodologically limited research field. *Pestalotiopsis* dominates both the occurrence and strength of total links, confirming that the literature is firmly pathogen-centered rather than system- or host-driven. The high prevalence of controlled studies underscores the strong reliance on laboratory-based and tightly regulated experimental designs, which, while valuable for mechanistic clarity, inherently limit ecological realism and field applicability. Although biological pest control appears frequently, its use reflects terminological generalization rather than conceptual accuracy, as *Pestalotiopsis* is a fungal pathogen; this highlights inconsistencies in the standardization of keywords in this field. More conceptually aligned terms—such as antifungal activity, biological control agent, and plant disease—show substantial connectivity, indicating a clear shift toward functional suppression of pathogenicity through enzymatic and metabolite mechanisms. The recurrent presence of endophytes, microbiology, genetics, and phylogeny suggests strong progress in mechanistic and taxonomic resolution, but their weak linkage to applied themes suggests limited downstream integration into formulation development, field validation, or integrated disease management systems. Collectively, this keyword architecture describes research domains that are scientifically robust at the mechanistic level but less developed translationally, thus defining a clear research boundary focused on scaling, environmental validation, and implementation of biological disease control strategies.

3.4. Evolution research in the control of *Pestalotiopsis* sp.

Figure 5 shows the shift in research themes related to the biological control of *Pestalotiopsis* sp. from 2005–2021 to 2022–2025. In the initial period, research was dominated by fundamental studies such as soil microflora, microbiology, *Pestalotiopsis*, endophytes, and early concepts of biological control, reflecting a focus on understanding basic biology and pathogen-microorganism interactions.

Entering the 2022–2025 period, research themes experienced strong consolidation with biological control as the primary focus, along with an increase in the number of publications. In this phase, a new theme emerged, namely antifungal activity, signaling a shift to the study of antagonistic mechanisms, including secondary metabolite production and enzymatic activity. Early themes such as soil microflora and endophytes are no longer isolated but are implicitly integrated into more applicable biological control approaches. Overall, this pattern reflects a paradigm shift from descriptive and biological research to biological control strategies based on mechanisms, effectiveness, and applicability, opening opportunities for formulation development, field validation, and sustainable implementation in plant disease management.

3.5. Biological control *Pestalotiopsis*

This synthesis review was initially based on 39 scientific articles specifically addressing the biological control of pathogens from the genus *Pestalotiopsis*. After further screening and filtering based on abstract relevance to ensure alignment with the research objectives, seven articles were selected for in-depth journal synthesis. This synthesis review is based on 39 scientific articles specifically addressing biological control of pathogens from the genus *Pestalotiopsis*. These studies evaluated a variety of antagonistic microorganisms, including *Trichoderma*, *Bacillus*, *Pseudomonas*, and other endophytic fungi, which have demonstrated the ability to inhibit pathogen growth through mechanisms such as antifungal metabolite production, competition, and induction of plant resistance

3.6. *Trichoderma* sp

(Baek et al., 2025; Gónzález-gaona et al., 2025) in their scientific articles stated that the *Trichoderma* spp.

strains evaluated exhibited antagonistic behavior against *Pestalotiopsis clavispora*, confirming their potential as biocontrol agents. Under field conditions, *Trichoderma* strains Tr 18 and 19 showed a tendency to reduce the incidence and severity of guava scab disease, comparable to conventional pesticides. The highest percentage of fruit damage was observed in strains 35 and 9, with damage levels of 7.97% and 7.10%, respectively, while strains 18 and 19 had lower damage levels of 2.20% and 2.33%. The effectiveness of the *Trichoderma* strains was not statistically significant due to the low overall disease incidence and variability between trees. The study found that the percentage of infection was low, with the highest infection in strains 35 and 9, indicating negative effectiveness compared to the control. Research Gap This study shows that although *Trichoderma* strains show potential as biocontrol agents, the lack of statistically significant differences between treatments suggests that further research is needed to confirm their effectiveness under various conditions. Multi-year validation studies in various regions are needed to strengthen the evidence for the effectiveness of *Trichoderma* strains in managing guava scab disease. There are unresolved issues regarding the variability of disease incidence and severity, which complicates the analysis of treatment effectiveness and may mask the true potential of biocontrol agents. All tested *Trichoderma* strains significantly inhibited pathogen growth, with the level of effectiveness varying significantly, with 11C-65-1 > RC > 29-8. Significant morphological changes were observed in both interacting fungi. The machine learning model was able to predict pathogen colony size with high accuracy (R^2 values on test data up to 0.94), with the identity of the specific *Trichoderma*–pathogen pair and the *Trichoderma* value being the most influential predictors. VOC compounds contribute to the inhibition of pathogen growth, and the use of larger amounts of *Trichoderma* biomass drastically increased the antagonistic effect, likely due to the combined action of VOCs and physical interactions. UVC pretreatment caused statistically significant morphological changes, but these were minimal under the test conditions used.

Figure 5. Thematic evolution

Furthermore, in vitro dual-culture antagonistic tests showed that *T. asperellum* Tric 33 suppressed the growth of *Poria hypolateritia*, *Rosellinia arcuata*, *Phellinus noxius* (root pathogens), *Lasiodiplodia theobromae*, *Fusarium solani* species complex, *Marasmius crinis*–equi (stem pathogen), *Colletotrichum* sp., and *Pestalotiopsis* sp. (leaf pathogens) on tea plants by 76–89%. Growth assessments showed that *T. asperellum* Tric 33 thrived at a pH of 4.5–5.5 and temperatures between 21–28°C. Incorporation of *T. asperellum* Tric 33 into integrated disease management strategies will enhance biodiversity, maintain soil health, and support climate-friendly cultivation practices (Gamlath et al., 2025).

3.7. *Bacillus velezensis*

(Sun et al., 2025) In their study, *Bacillus velezensis* GX1 was described as an effective biocontrol agent that significantly reduced the incidence of gray spot disease on *Polygonatum cyrtonema* by inhibiting the pathogen *Pestalotiopsis xuefengensis*. The results showed that GX1 effectively inhibited *P. xuefengensis* HJHB1, inhibiting pathogen growth by 74.97% in vitro and inhibiting disease development by 87.13% in field experiments. This strain produces antifungal metabolites, particularly lipastatin, which enhance plant resistance to *Pestalotiopsis* disease. The antifungal activity of lipopeptide extracts, particularly lipastatin and surfactin, was evaluated, demonstrating effectiveness against *P. xuefengensis* mycelial growth. The performance of biocontrol bacteria in outdoor environments remains uncertain, as factors such as competition from other microorganisms and environmental conditions may affect their efficiency. The stability of metabolites of biocontrol agents under various environmental conditions is not yet fully understood, although this is crucial for their commercial application. The specific mechanisms by which lipastatin exerts its antifungal effects, particularly in synergy with other metabolites, require further research. Differences in metabolite abundance between effective and ineffective *B. velezensis* strains need further exploration to identify key factors contributing to the effectiveness of biological control. This study did not address the long-term impact of biocontrol agent application in agricultural environments, which is crucial for sustainable disease management strategies.

B. velezensis isolate TS3B-45 demonstrated 80% in vitro inhibitory activity against *Colletotrichum gloeosporioides*, comparable to prochloraz (82%) and *Bacillus subtilis* ATCC 55614 (77%). Future research should focus on stabilizing and bioformulating *B. velezensis* strain TS3B-45 to improve its effectiveness as a biocontrol agent against post-harvest fungal pathogens (Reyes-Estebanez et al., 2020).

3.8. *Pseudomonas silvicola*

As mentioned disebutkan (Wang et al., 2025) PSM-6, an endophytic bacterium, exhibited excellent antagonistic activity against *NeoPestalotiopsis* camelliae-oleiferae, effectively protecting pine seedlings from pathogen infection. PSM-6's extracellular secondary metabolites caused the shrinkage and collapse of pathogenic hyphae, indicating a significant inhibitory effect. PSM-6 exhibited broad-spectrum antifungal activity against several phytopathogenic fungi, including *Fusarium graminearum*, *Botrytis cinerea*, and *Verticillium dahliae*. Disease index and mortality rates decreased with early treatment with PSM-6, indicating effective disease management. The antifungal mechanism of PSM-6 involves secondary metabolites that induce hyphal deformation, promote host growth, and enhance systemic resistance. Future studies can explore the broader application of PSM-6 in biological control, particularly its effectiveness against various plant pathogenic fungi beyond those already studied, such as *Fusarium graminearum* and *Botrytis cinerea*. Future research directions for identifying the mechanism of action of the secondary metabolite PSM-6 may provide insights into improving its antifungal properties and effectiveness in agricultural settings. Further studies could focus on the ecological impact of PSM-6 in natural environments, assessing its role in improving plant health and disease resistance across diverse ecosystems. Research could also aim to optimize PSM-6 application methods to maximize its biological control potential in commercial agriculture.

3.9. *Bacillus subtilis* subsp. spizizenii BL-59

(Duangkaew & Monkhung, 2021) used a dual culture test to determine the antifungal activity of isolate BL-59. The dual culture test showed that the antagonistic bacteria inhibited the mycelial growth of *Colletotrichum* sp. and *Pestalotiopsis* sp. by 49.31% and 42.55%, respectively. Morphological and biochemical studies of the antagonistic bacteria BL-59 showed that this isolate was classified as gram-positive, rod-shaped, and endospore-forming, and showed growth that survived under salinity stress and high temperature (45ºC). In addition, this strain produced catalase and oxidase enzymes. BL-59 was identified as having a very close relationship with *Bacillus subtilis* subsp. *spizizenii* (99.79%) using molecular identification based on the 16S rRNA gene. This study revealed that antagonistic bacteria can be used as an alternative option to control anthracnose disease by reducing chemical residues in agricultural production

3.10. Fusarium and Diaporte endophytic fungi

(Song et al., 2021) identified 71 endophytic fungi from blueberry roots, with FLR13 (*Pezicula* sp.) exhibiting significant antifungal effects and promoting plant growth. FLR13 increased blueberry plant height, leaf size, stem diameter, and fresh weight, demonstrating its potential for disease control and agricultural applications. A total of 71 endophytic fungi were isolated from blueberry roots, with *Diaporthe* and *Fusarium* being the most abundant genera. *Botrytis cinerea*, *Phomopsis* sp., *Botryosphaeria dothidea*, *Pestalotiopsis* sp., and *Fusarium oxysporum* were also identified. Isolate FLR13, classified as a *Pezicula* sp., exhibited an antifungal effect of over 60% against five blueberry pathogens. FLR13 treatment resulted in a 24.13% increase in plant height, 88.10% increase in leaf size, 43.32% increase in stem diameter, and 54.19% increase in plant fresh weight compared to seedlings not colonized by FLR13. The infection frequency (IF) of endophytic fungi in cultivated blueberries was only 15.3%, significantly lower than the 75–85% IF in wild blueberries. Future research directions include investigating the presence of documented secondary metabolites or novel compounds in FLR13 and their role in suppressing pathogen growth. Secondary metabolite profiles from other endophytes exhibiting antagonistic abilities are needed to understand the variation in antifungal effects. Further assessment of FLR13 performance across geographic locations and blueberry genotypes is essential to evaluate its broader application. Research should explore whether FLR13 can colonize a wider range of plant species, which could expand its use in various crop systems. Investigation of the underlying mechanisms by which FLR13 promotes blueberry growth, including phytohormone production, is recommended for future studies**.**

3.11. Research limitations

This study has several limitations that should be considered when interpreting the results. First, the bibliometric analysis was exclusively limited to publications indexed in the Scopus database and written in English. Second, the number of relevant articles synthesized by theme was only 39. The relatively small number of articles included in the final dataset (39 articles) reflects the stringent inclusion criteria applied, which, while improving data consistency and analytical clarity, may limit the comprehensiveness of the bibliometric network and the robustness of trend generalizations. Consequently, some emerging or niche research topics related to *Pestalotiopsis* biological control may not be fully reflected in the network visualization and keyword co-occurrence analysis. Third, bibliometric indicators such as keyword frequency, co-occurrence, and citations primarily reflect research structure and trends rather than the actual biological effectiveness or performance of biocontrol agents in the field. Most of the reviewed studies emphasized in vitro antagonistic tests or controlled experimental conditions, while long-term field trials, multi-site validation, and socio-economic evaluations were limited. This limits the review's ability to draw definitive conclusions regarding the practical scalability and consistency of biological control strategies under diverse agroecological conditions. Fourth, the narrative review component is inherently influenced by the availability and heterogeneity of published data. Differences in experimental design, host plant species, pathogen identification (including taxonomic revisions among *Pestalotiopsis*, Neo*Pestalotiopsis*, and *PseudoPestalotiopsis*), and evaluation parameters across studies limit direct comparison and synthesis of results. Furthermore, limited reporting on formulation technology, shelf-life stability, and interactions between biological agents and environmental factors limits a more in-depth analysis of commercialization potential. Finally, this study did not include quantitative meta-analyses or modeling approaches to estimate effect sizes or predict future disease dynamics under climate change scenarios. Therefore, while the findings provide a comprehensive overview of research trends and thematic gaps, they should be interpreted as descriptive and exploratory, rather than predictive.

4. Conclusion

This bibliometric and narrative review of 39 Scopus-indexed articles demonstrates a marked increase in research on the biological control of *Pestalotiopsis* spp., particularly since 2021, highlighting its growing relevance in sustainable disease management. The evidence consistently shows that fungal and bacterial antagonists effectively suppress the pathogen through multiple mechanisms, including antibiosis, resource competition, enzymatic degradation, and induction of host resistance. By integrating bibliometric mapping with mechanistic synthesis, this review provides a comprehensive perspective on research trends, key biocontrol agents, and emerging priorities. However, current findings are largely constrained to in vitro and controlled conditions, with limited field validation and insufficient data on formulation stability and long-term efficacy. Future research should emphasize field-based validation, bioformulation optimization, and integration into integrated disease management frameworks to ensure practical applicability. This review establishes a robust scientific basis to support the advancement of sustainable control strategies against *Pestalotiopsis*-associated diseases.

References

Alchemi, P. J. K., & Jamin, S. (2022). Impact of *Pestalotiopsis* leaf fall disease on leaf area index and rubber plant production. In J. N., A. F., R. S. H., W. M., S. E., & R. R. (Eds.), *IOP Conference Series: Earth and Environmental Science* (Vol. 995, Issue 1). IOP Publishing. https://doi.org/10.1088/1755-1315/995/1/012030

Araujo, L., Ferreira Pinto, F. A. M., de Andrade, C. C. L., Mituti, T., Falkenbach, B. R., Gomes, L. B., & Duarte, V. (2023). *Pestalotiopsis trachycarpicola* causes leaf spot disease on blueberry in Santa Catarina, Brazil. *Australasian Plant Disease Notes, 18*(1). https://doi.org/10.1007/s13314-023-00500-7

Ávila-Hernández, J. G., León-Ramírez, C. G., Abraham-Juárez, M. R., Tlapal-Bolaños, B., Olalde-Portugal, V., Délano-Frier, J. P., Martínez-Antonio, A., & Aguilar-Zárate, P. (2025). *NeoPestalotiopsis* spp.: A threat to strawberry production and management. *Horticulturae, 11*(3), 288. https://doi.org/10.3390/horticulturae11030288

Baek, I., Bhatt, J., Jang, J. H., Lim, S., Lovelace, A., Cha, M., Lakshman, D., Kim, M. S., Meinhardt, L. W., Park, S., & Ahn, E. (2025). Dissecting *Trichoderma* antagonism: Role of strain identity, volatiles, biomass, and morphology in suppressing cacao pathogens. *Biological Control, 207*. https://doi.org/10.1016/j.biocontrol.2025.105807

Chandoliya, R., Sharma, S., & Sharma, V. (2023). Role of microbial oxidative enzymes in biological control of plant pathogens. In *Microbial Oxidative Enzymes: Biotechnological Applications* (pp. 129–154). De Gruyter. https://doi.org/10.1515/9783111062235-007

Chen, L., Xu, L., Li, X., Wang, Y., Feng, Y., & Huang, G. (2023). The diseases and pests of rubber tree and their natural control potential: A bibliometric analysis. https://doi.org/10.3390/agronomy13081965

Cucu, M. A., Choudhary, R., Trkulja, V., Garg, S., & Matić, S. (2025). Utilizing environmentally friendly techniques for the sustainable control of plant pathogens: A review. *Agronomy, 15*(7). https://doi.org/10.3390/agronomy15071551

Duangkaew, P., & Monkhung, S. (2021). Antifungal activity of *Bacillus subtilis* subsp. *spizizenii* BL-59 to control some important postharvest diseases of mango fruits (*Mangifera indica* L.). *International Journal of Agricultural Technology, 17*(6), 2053–2066.

Escalante, M., Damas, D., Márquez, D., Gelvez, W., Chacón, H., Díaz, A., & Moreno, B. (2010). Diagnosis and evaluation of *Pestalotiopsis*, and insect vectors, in an oil palm plantation at the South of Maracaibo Lake, Venezuela. *Bioagro, 22*(3), 211–216.

Gamlath, R. D. S. M., Gunawardana, K. L. S. C., Karunajeewa, D. G. N.

P., Mahadevan, N., Senanayake, P. D., Rajapakse, S., & Sinniah, G. D. (2025). *Trichoderma asperellum* Tric 33 as a broad-spectrum biopesticide against multiple diseases of tea (*Camellia sinensis* (L.) O. Kuntze). *BioControl*. https://doi.org/10.1007/s10526-025-10370-w

González-Gaona, E., Lira-Ramos, K. V. de, & Sánchez-Lucio, O. L. R. R. (2025). Efectividad biológica de cepas de *Trichoderma* contra el clavo de la guayaba (*Pestalotiopsis clavispora*) en condiciones *in vitro* y de campo. *Tropical and Subtropical Agroecosystems, 28*, 141. https://doi.org/10.56369/tsaes.6451

Gopi, R., Kalita, H., Avasthe, R. K., Yadav, A., Singh, M., & Thapa, D. (2018). Does *Pestalotiopsis royenae* cause leaf streak of large cardamom. *Current Science, 114*(10), 2155–2160. https://doi.org/10.18520/cs/v114/i10/2155-2160

Gualberto, G. F., Catarino, A. D. E. M., Sousa, T. F., Cruz, J. C., Hanada, R. E., Caniato, F. F., & Silva, G. F. (2021). *PseudoPestalotiopsis gilvanii* sp. nov. and *NeoPestalotiopsis formicarum* leaf spot pathogens from guarana plant: A new threat to global tropical hosts. *Phytotaxa, 489*(2), 121–139. https://doi.org/10.11646/phytotaxa.489.2.2

Jayawardena, R. S., Zhang, W., Liu, M., Maharachchikumbura, S. S. N., Zhou, Y., Huang, J., Nilthong, S., Wang, Z., Li, X., Yan, J., & Hyde, K. D. (2015). Identification and characterization of *Pestalotiopsis*-like fungi related to grapevine diseases in China. *Fungal Biology, 119*(5), 348–361. https://doi.org/10.1016/j.funbio.2014.11.001

Karamova, K. O., Kuryntseva, P. A., Fomin, V. P., & Selivanovskaya, S. Y. (2019). Biological agents to control plant wilt. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management (SGEM), 19*(5.2), 193–202. https://doi.org/10.5593/sgem2019/5.2/S20.025

Keith, L. M., & Zee, F. T. (2010). Guava diseases in Hawaii and the characterization of *Pestalotiopsis* spp. affecting guava. *Acta Horticulturae, 849*, 269–276. https://doi.org/10.17660/ActaHortic.2010.849.31

Kumar, S., Sindhu, S. S., & Kumar, R. (2023). Microbial endophytes: Prospects in biological control of plant pathogens and plant growth stimulation for sustainable agriculture. In *Plant Endophytes and Secondary Metabolites* (pp. 375–422). Elsevier. https://doi.org/10.1016/B978-0-443-13365-7.00015-4

Lekete, E., Osekre, E. A., & Andoh-Mensah, E. (2019). Report on outbreak and *in vitro* management of leaf spots disease caused by *Pestalotiopsis* sp. on oil palm seedlings in nurseries in Ghana. *Malaysian Journal of Microbiology, 15*(5), 419–424. https://doi.org/10.21161/mjm.180170

Martínez, L. C., & Plata-Rueda, A. (2013). Lepidoptera vectors of *Pestalotiopsis* fungal disease: First record in oil palm plantations from Colombia. *International Journal of Tropical Insect Science, 33*(4), 239–246. https://doi.org/10.1017/S1742758413000283

McQuilken, M. P., & Hopkins, K. E. (2004). Biology and integrated control of *Pestalotiopsis* on container-grown ericaceous crops. *Pest Management Science, 60*(2), 135–142. https://doi.org/10.1002/ps.792

Pandey, A. K., Sinniah, G. D., Yadav, S., & Maharachchikumbura, S. S. N. (2024). *Pestalotiopsis*-like species: Host network and lifestyle on tea crop. *Fungal Biology Reviews, 47*. https://doi.org/10.1016/j.fbr.2023.100340

Ren, H.-Y., Li, G., Qi, X.-J., Fang, L., Wang, H.-R., Wei, J.-G., & Zhong, S. (2013). Identification and characterization of *Pestalotiopsis* spp. causing twig blight disease of bayberry (*Myrica rubra* Sieb. & Zucc.) in China. *European Journal of Plant Pathology, 137*(3), 451–461. https://doi.org/10.1007/s10658-013-0255-y

Reyes-Estebanez, M., Sanmartín, P., Camacho-Chab, J. C., De La Rosa-García, S. C., Chan-Bacab, M. J., Aguila-Ramírez, R. N., Carrillo-Villanueva, F., de la Rosa-Escalante, E., Arteaga-Garma, J. L., Serrano, M., & Ortega-Morales, B. O. (2020). Characterization of a native *Bacillus velezensis*-like strain for the potential biocontrol of tropical fruit pathogens. *Biological Control, 141*. https://doi.org/10.1016/j.biocontrol.2019.104127

Rybus-Zając, M. (2005). Oxidative stress generation in *Taxus baccata* leaves affected by *Pestalotiopsis funerea* under sunny and shaded conditions. *Dendrobiology, 54*, 51–56.

Song, X., Li, Y., Hu,Y., Guo, W., Wu, Z., Zhang, Y., & Cao, Z. (2021). Endophytes from blueberry roots and their antifungal activity and plant growth enhancement effects. *Rhizosphere, 20*. https://doi.org/10.1016/j.rhisph.2021.100454

Sun, L., Deng, G. L., Wu, H. L., He, Q., Hu, S. H., Li, J. Y., Li, X. Y., Meng, S., He, A. N., Tian, Y. Q., Chen, X., & Li, S. H. (2025). Biocontrol of gray spot disease on *Polygonatum cyrtonema* Hua by *Bacillus velezensis* GX1. *Biological Control, 201*. https://doi.org/10.1016/j.biocontrol.2025.105704

Vasić, T., Jevremović, D., Krnjaja, V., Leposavić, A., Andjelković, S., Živković, S., & Paunović, S. (2017). Morphological description and molecular detection of *Pestalotiopsis* sp. on hazelnut in Serbia. *Spanish Journal of Agricultural Research, 15*(3). https://doi.org/10.5424/sjar/2017153-11297

Wang, X.-Y., Xu, F., Li, M., Latif, M. F., Li, H., & Chen, F. (2025). Endophytic bacteria in forest protection: *Pseudomonas silvicola* controls pine needle blight in Masson pine. *Forests, 16*(4). https://doi.org/10.3390/f16040650

Zhou, L., Li, X., Kotta-Loizou, I., Dong, K., Li, S., Ni, D., Hong, N., Wang, G., & Xu, W. (2021). A mycovirus modulates the endophytic and pathogenic traits of a plant-associated fungus. *The ISME Journal, 15*(7), 1893–1906. https://doi.org/10.1038/s41396-021-00892-3