AGRIWAR JOURNAL
MASTER OF AGRICULTURAL SCIENCE WARMADEWA UNIVERSITY
E-ISSN: 2808-1137, **P-ISSN**: 2808-1323

Vol. 5, **No.** 2, **Des 2025**, **Page** 103-112
DOI: https://doi.org/10.22225/agriwar.5.2.2025.103-112

Biopesticides to Control Anthracnose Disease in Chili Pepper (*Capsicum annuum* L.): A Review

Ni Kadek Desy Andya Dewi*; Ni Luh Putu Sulis Dewi Damayanti; Anak Agung Sagung Putri Risa Andriani
Agrotechnology Study Program, Faculty of Agriculture, Science and Technology, Warmadewa University, Denpasar, Bali, Indonesia.
*Corresponding author: desyandya@warmadewa.ac.id.

Abstract
Anthracnose disease is one of the most destructive diseases affecting chili pepper (Capsicum annuum L.). The impact of anthranose on production worldwide results in significant yield and quality losses during both pre-harvest and post-harvest stages. Control of this disease has relied use traditional technic with synthetic fungicides. Synthetic fungicides have caused pathogen resistance, environmental contamination, and food safety concerns. Therefore, biopesticides are considered an environmentally friendly and sustainable alternative. This review aims to critically summarize recent studies published between 2015 and 2025 on the application of biopesticides to controlling anthracnose disease in chili pepper. Scientific literature was collected from major databases, including Scopus, ScienceDirect, and Google Scholar. The review highlights the effectiveness of biopesticides from microbial and botanical pesticides. Microbial pesticides such as Trichoderma spp., Bacillus, and Pseudomonas spp. Contribute to disease suppression by producing antimicrobial metabolites and inducing systemic resistance in host plants. Botanical pesticides based on plant extracts and essential oils have antifungal activity by inhibiting spore germination, disrupting fungal cell structures, and antimicrobial chemical compounds. Although biopesticides potential to control anthracnose disease, but remains inconsistent due to environmental factors and formulation constraints. Therefore, improved formulation technologies and integration into integrated disease management strategies are essential to enhance their reliability and adoption in sustainable chili production systems.

Keywords: *biopesticides; anthracnose disease; chili pepper.*

1. Introduction

Plant diseases are one of the main limiting factors in modern horticultural production, and red chili peppers (*Capsicum annuum* L.) are no exception. For decades, farmers have relied on synthetic chemical fungicides to control fungal pathogens because of their rapid effectiveness and broad spectrum [1]. However, the intensive use of chemical pesticides has had various negative impacts, including pathogen resistance to fungicides, a decline in non target organism populations, and the accumulation of harmful residues in food products and the environmen. In addition, international regulatory pressure on chemical residues in chili peppers has encouraged the search for safer and more sustainable disease control alternatives [2].

Chili peppers are a high-value horticultural commodity and an important part of the global diet. Chili peppers are not only a key kitchen spice, but also an important source of vitamin C, carotenoids, and antioxidants that contribute to human nutrition [3]. In many developing countries, chili peppers also serve as a strategic export commodity that supports the income of small farmers. However, chili pepper productivity is often hampered by disease outbreaks, particularly anthracnose caused by the *Colletotrichum* spp. Complex. This pathogen attacks chili peppers during the pre-harvest and post-harvest phases, causing rapidly developing necrotic spots and significantly reducing the quality and quantity of the harvest [4]. Control of anthracnose in the field still almost exclusively uses chemical fungicides. However, many reports indicate a decline in the effectiveness of certain fungicides due to the emergence of mutations and resistance in the pathogen populations. In addition, consumer concerns about chemical residues on agricultural products and the need for environmentally friendly agricultural practices have prompted the search for safe and sustainable alternative approaches [5].

Biopesticides have emerged as a promising solution in plant disease management, including pepper anthracnose. In general, biopesticides are agents or compounds derived from living organisms or natural products, such as antagonistic microorganisms and plant extracts, which are used to suppress pests and plant pathogens biologically [6]. This definition includes products derived from microbes, their metabolic compounds, and botanical materials that have antimicrobial activity. Among scientists, biopesticides are classified into microbial biopesticides, botanical biopesticides, and other agents that can stimulate plant growth or resistance to biotic stress. Biopesticides tend to be more specific to target organisms, degrade quickly in the environment, and pose a lower risk of residues to humans and non-target organisms [7]. In the context of anthracnose disease, many studies report that antagonistic microorganisms such as *Trichoderma* spp. and *Bacillus* spp. can suppress *Colletotrichum* sp. through mechanisms of space and nutrient competition, antibiosis, mycoparasitism, and induction of systemic resistance in host plants [8], [9]. Additionally, plant extracts from species such as neem (*Azadirachta indica*), clove (*Syzygium aromaticum*), and garlic (*Allium sativum*) have been reported to have effective antifungal activity against *Colletotrichum*, primarily through the inhibition of spore germination and the formation of infection tissues [10], [11]. Bioactive components of plants, such as phenols, alkaloids, terpenoids, saponins, and other volatile compounds, are often responsible for these antifungal properties. These compounds are capable of inhibiting critical processes of pathogen infection, including conidia germination, mycelium development, and host tissue penetration [12].

Based on this background, this review article was compiled to present a summary of the latest scientific information on the role of microbial pesticides and plant extracts in controlling anthracnose disease in red chili peppers. The main focus of the discussion includes the types of biopesticides reported to be effective, their biological mechanisms of action, effectiveness under laboratory and field conditions, as well as the challenges and prospects for developing biopesticides as part of a sustainable anthracnose disease management strategy. His review provides a comprehensive and critical synthesis of microbial and botanical biopesticides against chili anthracnose, highlighting comparative effectiveness, mechanisms of action, and formulation challenges to guide future research and application.

2. Materials and Methods

This study is a review that focuses on the application of biopesticides for controlling anthracnose disease in chili pepper. The review aims to compile, analyze, and synthesize recent research findings on the effectiveness of various plant extracts and natural compounds as antifungal agents that have the potential to replace or reduce the use of synthetic chemical fungicides in sustainable agricultural systems.

The references used in this review were obtained through a systematic search of several international scientific databases, including Scopus, Google Scholar, and ScienceDirect, as well as other reputable web journals relevant to the fields of plant pathology and plant protection. The literature search was conducted using keywords such as "biopesticides," "microbial pesticide," "plant extracts," "anthracnose," and "chili pepper." The selected articles cover publications from 2015 to 2025, thereby representing the most recent developments in this research area over the past decade.

3. Results and Discussion

3.1 Types of Biopesticides Used Against Anthracnose

Control of anthracnose in chili peppers (*Capsicum annuum* L.) using biopesticides involves various groups of biological agents based on their origin, mechanism of action, and properties. In

DOI: https://doi.org/10.22225/agriwar.5.2.2025.103-112

general, the biopesticides used include fungal, bacterial, and botanical biopesticides. Each type has specific potential and mechanisms of action in suppressing infection by *Colletotrichum* spp., and other fungal pathogen that causes anthracnose.

1. Fungal Pesticides

Fungal biopesticides are fungus-based antagonistic microbes used to suppress the growth and development of *Colletotrichum* spp. Several fungal genera that are often reported in biological control studies include *Trichoderma*. *Trichoderma* spp. Fungi are one of the most widely studied biocontrol agents because they have multiple mechanisms of action, such as antibiosis, mycoparasitism, and competition for space and nutrients [8]. Antibiosis occurs when *Trichoderma* produces lytic enzymes such as chitinase and β-1,3-glucanase that degrade the cell walls of pathogenic fungi (*Colletotrichum* spp.) as well as antifungal metabolites that directly inhibit mycelium growth [13]. In addition, Trichoderma can compete with pathogenic fungi for space and nutrients and stimulate plant defense responses through the induction of systemic resistance. Other studies have shown that antagonistic fungal formulations increase the resistance of chili plants to anthracnose attacks through the improvement of rhizosphere microbiota and increased plant defense enzyme activity [14].

2. Bacterial Pesticides

Bacterial biopesticides for anthracnose control generally originate from the genera *Bacillus*, Pseudomonas, and Streptomyces. These bacteria have several antagonistic mechanisms against fungal pathogens, including the production of antimicrobial compounds, competition for space and nutrients, and induction of plant defense responses (Köhl et al., 2019; Tyagi et al., 2024). The genus *Bacillus,* especially *Bacillus subtilis* and *Bacillus amyloliquefaciens*, is known to produce biosurfactant lipopeptides such as surfactin, iturin, and fengicin, which can damage fungal cell membranes and inhibit the germination of Colletotrichum spp. spores (Ongena & Jacques, 2008; Medeot et al., 2020). These lipopeptide compounds create pores in the pathogen membrane, causing cell contents to leak and the fungus to die. In addition, several strains of Pseudomonas fluorescens produce antifungal metabolites such as phenazine and pyoluteorin, which show strong activity in suppressing the growth of *Colletotrichum* spp. (Köhl et al., 2019). Streptomyces spp. has also been studied for its ability to produce natural antibiotics that are effective against various fungal pathogens. The use of antagonistic bacterial consortia shows more consistent results in the field due to the synergism between the antimicrobial compounds produced and their improved colonization ability. Recent research also highlights the role of bacteria in stimulating Induced Systemic Resistance (ISR) in plants, increasing defense enzyme activity, and reducing the severity of anthracnose attacks (Tyagi et al., 2024).

3. Botanical Pesticides

Botanical biopesticides are plant-derived bioactive compounds such as essential oils, flavonoids, alkaloids, terpenoids, and phenols that exhibit natural antifungal activity against plant pathogens. Their main advantages include biodegradability, low toxicity to non-target organisms, and availability from local plant resources. Several plants, including neem (*Azadirachta indica*), clove (Syzygium aromaticum), and garlic (*Allium sativum*), have been reported to be effective against *Colletotrichum* spp. [10], [15]. Active compounds such as azadirachtin, citral, and eugenol inhibit spore germination, disrupt fungal cell membranes, and suppress mycelial growth, resulting in fungistatic or fungicidal effects in laboratory and field studies [16]. Moreover, combining botanical extracts with antagonistic microbes may enhance synergistic effects, highlighting their potential in integrated biopesticide strategies for anthracnose control [17].

3.2 Effectiveness of Biopesticides in Controlling

This subsection presents the effectiveness of biopesticides in controlling anthracnose disease in chili peppers based on various research results using microbial pesticides and botanical pesticides. Biopesticides are gaining attention as an environmentally friendly control alternative because they are biodegradable, relatively safe for non-target organisms, and support sustainable agriculture. The effectiveness of biopesticides in these studies is grouped into two main categories.

Microbial pesticides, which include antagonistic bacteria and fungi. These microorganisms have been reported to suppress the growth of Colletotrichum sp. and other fungi that cause anthracnose through various mechanisms, including antibiosis, competition for space and nutrients, mycoparasitism, and induction of plant resistance. This section presents ten examples of microbial agents from various studies that show high antagonistic activity against pathogens, both through in vitro tests and in vivo tests on chili peppers or plants, as shown in Table 1.

Table 1. 10 examples of microbial pesticides for controlling anthracnose disease in chili peppers.

No	Biopesticide/Agen	Pathogen Target	Method	Antagonis Activity	References
1	*Streptomyces lactacystinicus*	*Coletrotichum scovillei*	Dual culture assay	Inhibitory activity to 74,42%	[18]
2	*Bacillus velezensis* LY7	*Coletrotichum scovillei*	Dual culture assay	Inhibitory activity to 70,93%	[9]
3	*Bacillus subtilis* AKP	*Colletotrichum capsici*	Dual culture assay	Inhibitory activity to 61,5 %	[19]
4	*Trichoderma asperellum* NST-009	*Colletotrichum gloeosporioides* PSU-03	Dual culture assay	Inhibitory activity to 62,07%	[8]
5	*Bacillus subtilis* PTS-394	*Fusarium solani*	Dual culture assay	*B. subtilis* PTS-394 showed a good biocontrol activity against *Fusarium solani* at 74.43 %	[20]
6	*Paenibacillus polymyxa* C1	*Colletotrichum scovillei* SGCR	Invivo analysis on Chili Pepper Fruit	Formulation F6 with concentration 3% was able to inhibite 85,11%.	[21]
7	*Trichoderma atroviride* ATR697	*Colletotrichum acutatum*	Dual culture assay	100% inhibition value.	[22]
8	*Trichoderma koningiopsis* PSU3-2	*Colletotrichum gloeosporioides*	Dual culture assay	Inhibitory activity of 79.57%	[13]
9	*Streptomyces griseocarneus* R132	*Colletotrichum gloeosporioides MPU99*	Dual culture assay	Inhibitory activity to 70,45%	[23]
10	*Trichoderma asperellum* Tc-Jjr-02	*Colletotrichum* sp.	Dual culture assay	Inhibitory activity of 61.97%	[24]

Plant-based pesticides, derived from plant extracts and essential oils, have also been reported to be effective in inhibiting the development of Colletotrichum spp. Bioactive compounds such as phenolics, flavonoids, terpenoids, and alkaloids play a role in inhibiting spore germination, damaging fungal cell membranes, and suppressing mycelium growth. This subsection compiles twenty examples of botanical pesticides from various literature that show inhibitory ability against pepper anthracnose in in vitro, in vivo, and post-harvest tests, with varying levels of effectiveness depending on the type of plant, extraction method, and concentration used.

DOI: https://doi.org/10.22225/agriwar.5.2.2025.103-112

Table 2. 10 examples of botanical pesticides for controlling anthracnose disease in chili peppers.

No	Biopesticide	Pathogen Target	Method	Inhibitory activity	References
1	Mimba extract (*Azadirachta* sp.)	*Colletotrichum acutatum*	In vitro Antifungal activity assay	Inhibitory activity of 70.20%	[25]
2	Basil extract (*Ocimum basilicum*)	*Colletotrichum gloeosporioides*	In vitro Antifungal activity assay	Inhibitory activity of 43.13%	[15]
3	*Acalypha indica* extract	*Colletotrichum dematium*	In vitro Antifungal activity assay	Inhibitory activity of 100% at a concentration of 20%	[26]
4	Garlic extract (*Allium sativum*)	*Colletotrichum capsici*	In vitro Antifungal activity assay	Inhibitory activity to 100%	[16]
5	*Syzygium aromaticum* (clove) extract	*Colletotrichum* sp	In vitro colony growth inhibition	Inhibitory activity of 91.7%	[17]
6	*Pangium edule* extract	*Colletotrichum* sp	In vitro colony growth inhibition	Inhibitory activity of 75%	[17]
7	*Eupatorium odoratum* extract	*Colletotrichum capsici*	Antifungal activity assay	Inhibitory activity of 91.97% at a concentration of 20 mg/ml,	[27]
8	*Allium sativum* (garlic) extract	*Colletotrichum* sp	Antifungal activity assay	Inhibitory activity of 53.33%	[28]
9	Extracts of neem (*Azadirachta indica*)	*Colletotrichum capsici*	Antifungal activity assay	Inhibitory activity of 43.37%	[11]
10	Cinnamon leaf extract	*Colletotrichum acutatum*	Antifungal activity assay	Inhibitory activity of 100% at 1.5% concentration	[10]

3.3 Mode of Action

Anthracnose disease in chili peppers is one of the major diseases that causes significant losses both in the pre-harvest and post-harvest phases. This pathogen can form latent infections and produce large numbers of conidia, so control with chemical fungicides is often ineffective and risks causing resistance. Therefore, the use of biopesticides is a sustainable alternative approach because they work through various complex and complementary biological mechanisms, as illustrated in Figure 1 [29], [30], [31].

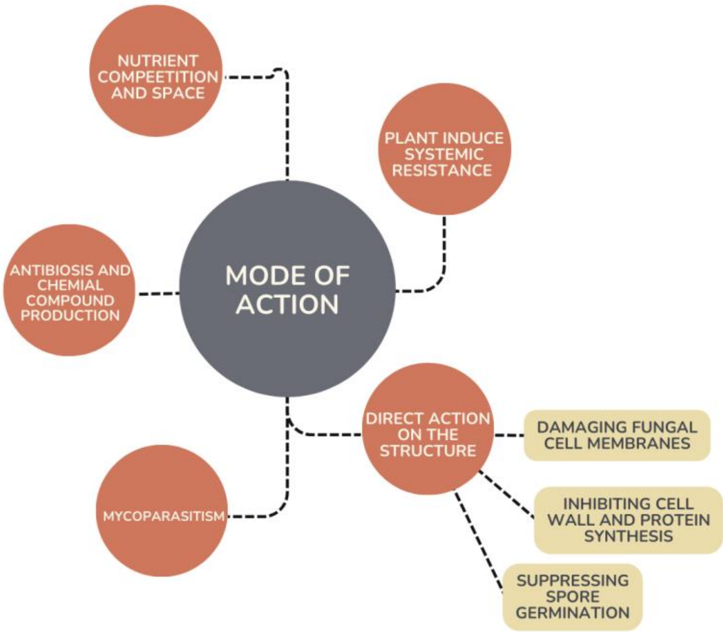

Figure 1. Mode of Action

1. Nutrient Competition and Space

Nutrient and space competition are very important initial mechanisms in the success of biocontrol agents. Antagonistic microorganisms such as *Bacillus* spp., *Pseudomonas* spp., and *Trichoderma* spp. are able to quickly colonize the surface of leaves, fruits, and the rhizosphere of chili plants, thus occupying the same ecological niche as *Colletotrichum* spp. [22]. Biocontrol agents absorb essential nutrients such as carbon, nitrogen, and mineral ions faster than pathogens, causing nutrient limitations for Colletotrichum. This condition directly impacts the inhibition of conidia germination, appressorium formation, and pathogen mycelium growth [15][13]. In addition, some antagonistic bacteria are capable of forming biofilms on plant tissue surfaces, which function as physical barriers against pathogen penetration [32].

2. Antibiosis dan Chemical Compound Production

Antibiosis is one of the main mechanisms of microbial biopesticides in suppressing Colletotrichum spp. and other fungi. Bacteria from the genus *Bacillus* produce various secondary metabolites, such as lipopeptides (iturin, fengicin, and surfactin), which are fungistatic and fungicidal. These compounds work by damaging the integrity of the fungal cell membrane, causing cytoplasmic leakage, and ultimately triggering the death of the pathogenic cell [33]. Antagonistic fungi such as *Trichoderma* spp. also produce peptibols and hydrolytic enzymes, including chitinase and β-1,3-glucanase, which degrade the cell walls of pathogenic fungi. This antibiosis activity has been shown to significantly inhibit the growth of mycelium and spore germination of *Colletotrichum*, especially during the early stages of infection [13].

3. Mycoparasitism by Antagonistic Fungi

Mycoparasitism is a direct mechanism primarily carried out by antagonistic fungi such as *Trichoderma harzianum* and *T.* viride. In this mechanism, the antagonistic fungus recognizes *Colletotrichum* hyphae through chemical signals, then grows toward the pathogen, entangles the mycelium, and penetrates the pathogen's cell wall using lytic enzymes. The process of cell wall degradation causes structural damage to *Colletotrichum* hyphae, leading to mycelium collapse and pathogen death. Mycoparasitism is highly effective in high-humidity environments, which support the growth of antagonistic fungi, and plays an important role in reducing pathogen inoculum in the field [34].

4. Direct Action on the Structure

In addition to microbial biopesticides, plant extracts also play an important role in controlling chili anthracnose. Plant extracts contain various bioactive compounds, such as phenols, flavonoids, alkaloids, terpenoids, and essential oils, which have antifungal activity against *Colletotrichum* spp. [27]. These compounds work through several mechanisms, including [35]:

a. Damaging the fungal cell membrane, thereby disrupting osmotic balance and cell metabolism;
b. Inhibiting cell wall and protein synthesis, which causes mycelium growth to be inhibited.
c. Suppressing spore germination and appressorium formation, thereby reducing the pathogen's ability to infect plant tissues.

Some plant extracts are also volatile and can inhibit pathogens without direct contact, making them potentially useful as control agents in the post-harvest phase to suppress fruit rot caused by anthracnose [26].

5. Plant Induce Systemic Resistance

In addition to direct mechanisms against pathogens, microbial biopesticides and plant extracts are also capable of enhancing the resistance of chili plants through the induction of systemic resistance, known as Induced Systemic Resistance (ISR) or Systemic Acquired Resistance (SAR) [36]. Biocontrol agents and natural compounds such as chitosan can activate plant defense signaling pathways mediated by salicylic acid, jasmonate, and ethylene. Activation of these pathways increases the activity of defense enzymes, such as peroxidase, polyphenol oxidase, and phenylalanine ammonia-lyase, and promotes the accumulation of phenolic compounds and lignin, which strengthen plant cell walls[35]. This induction of resistance is crucial in controlling anthracnose, given that Colletotrichum spp. Often infect plants latently. Plants with activated defense systems are able to limit pathogen development before disease symptoms appear.

3.4 Challenges and Future Prospects

Although numerous studies have demonstrated the potential of microbial biopesticides and plant extracts to suppress anthracnose in chili peppers, their field application still faces major challenges. The most critical issue is the inconsistency between in vitro efficacy and field performance, largely due to environmental variability and interactions with native microorganisms[37]. In microbial biopesticides, limited survival and colonization under stress conditions such as UV radiation and drought often reduce their effectiveness, while the predominant use of single strains fails to reflect the complex field ecosystem [38]. For plant extract-based products, the lack of standardization of active compounds, the use of crude extracts, and potential phytotoxicity at high concentrations hinder reproducibility and commercial development. In addition, the adaptive potential of *Colletotrichum* spp. to long-term biopesticide exposure remains poorly understood [7].

Prospects lie in shifting research toward mechanism- and system-based approaches, including the development of functionally complementary microbial consortia and advanced formulations such as microencapsulation and nano-delivery systems to enhance stability and efficacy [38]. Moreover, long-term multi-location field trials and the integration of biopesticides into Integrated Disease Management (IDM) strategies are essential for achieving sustainable anthracnose control and reducing reliance on synthetic fungicides. Overall, while biopesticides offer a promising eco-friendly alternative, their successful adoption depends on bridging the gap between laboratory results, field effectiveness, and practical agricultural needs.

4. Conclusion

Anthracnose continues to pose a serious challenge in chili pepper production. Based on studies published between 2015 and 2025, biopesticides derived from fungi, bacteria, and plant extracts have demonstrated considerable potential to suppress anthracnose through multiple mechanisms, including antibiosis, mycoparasitism, competition, and induction of plant resistance. Compared with synthetic fungicides, biopesticides offer advantages in terms of environmental safety and sustainability. However, their inconsistent performance under field conditions and limitations in formulation stability remain key challenges. Future efforts should focus on developing stable formulations, microbial consortia, and integrated disease management approaches to enhance the effectiveness and practical adoption of biopesticides for sustainable anthracnose control in chili pepper.

Reference

[1] Barchenger, D. W., Lamour, K. H., & Bosland, P. W. (2018). Challenges and strategies for breeding resistance in *Capsicum annuum* to the multifarious pathogen, *Phytophthora capsici*. Frontiers in Plant Science, 9, 1–16. https://doi.org/10.3389/fpls.2018.00628

[2] Park, M., Kim, S., Bae, S., & Im, M. (2024). International pesticide monitoring data for safety management. Toxics, 2, 1–11.

[3] Mohd Ali, M., Khalid, N. I., Wondi, M. H., Haris, N. I. N., & Megat Ahmad Azman, P. N. (2025). Exploring the nutritional values, volatile compounds, health benefits, and potential food products of chilli (*Capsicum annuum*): A comprehensive review. Food Chemistry, 490, 145091. https://doi.org/10.1016/j.foodchem.2025.145091

[4] Yanty, D. P., Trizelia, Darnetty, & Trisno, J. (2024). Anthracnose disease attacks chili plants in West Sumatra. International Journal of Advanced Science, Engineering and Information Technology, 14(5), 1683–1687. https://doi.org/10.18517/ijaseit.14.5.11266

[5] Islam, T., Danishuddin, Tamanna, N. T., Matin, M. N., Barai, H. R., & Haque, M. A. (2024). Resistance mechanisms of plant pathogenic fungi to fungicides, environmental impacts of fungicides, and sustainable solutions. Plants, 13(19), 1–27. https://doi.org/10.3390/plants13192737

[6] Khursheed, A., et al. (2022). Plant-based natural products as potential eco-friendly and safer biopesticides: A comprehensive overview of their advantages over conventional pesticides, limitations, and regulatory aspects. Microbial Pathogenesis, 173, 105854. https://doi.org/10.1016/j.micpath.2022.105854

[7] Kumar, J., Ramlal, A., Mallick, D., & Mishra, V. (2021). An overview of some biopesticides and their importance in plant protection for commercial acceptance. Plants, 10(6), 1–15. https://doi.org/10.3390/plants10061185

[8] Boukaew, S., Chumkaew, K., Petlamul, W., Srinuanpan, S., Nooprom, K., & Zhang, Z. (2024). Biocontrol effectiveness of *Trichoderma asperelloides* SKRU-01 and *Trichoderma asperellum* NST-009 on postharvest anthracnose in chili pepper. Food Control, 163, 110490. https://doi.org/10.1016/j.foodcont.2024.110490

[9] Zhong, J., Wu, X., Guo, R., Li, J., Li, X., & Zhu, J. (2024). Biocontrol potential of *Bacillus velezensis* HG-8-2 against postharvest anthracnose on chili pepper caused by *Colletotrichum scovillei*. Food Microbiology, 124, 104613. https://doi.org/10.1016/j.fm.2024.104613

[10] Darmadi, A. A. K., Suriani, N. L., Ginantra, I. K., & Sudirga, S. K. (2022). Effectiveness of cinnamon leaf extract to control anthracnose disease on large chilies in Bali, Indonesia. Biodiversitas, 23(6), 2859–2864. https://doi.org/10.13057/biodiv/d230611

[11] Chauhan, A., & Yadav, V. (2022). In vitro evaluation of plant extracts and fungicides against *Colletotrichum capsici* causing anthracnose disease of chilli. [Journal], 14(4), 720–725.

[12] Dantas, T. dos S., Machado, J. C. B., Ferreira, M. R. A., & Soares, L. A. L. (2025). Bioactive plant compounds as alternatives against antifungal resistance in Candida strains. Pharmaceutics, 17(6), 1–25. https://doi.org/10.3390/pharmaceutics17060687

[13] Ruangwong, O. U., Pornsuriya, C., Pitija, K., & Sunpapao, A. (2021). Biocontrol mechanisms of *Trichoderma koningiopsis* PSU3-2 against postharvest anthracnose of chili pepper. Journal of Fungi, 7(4). https://doi.org/10.3390/jof7040276

[14] Law, C. X., Hashim, N., Ismail, S. I., Jahari, M., & Al Riza, D. F. (2025). A review on anthracnose disease caused by *Colletotrichum* spp. in fruits and advances in control strategies. International

Journal of Food Microbiology, 442, 111397. https://doi.org/10.1016/j.ijfoodmicro.2025.111397
[15] Rizki, A. Z., Choliq, F. A., & Martosudiro, M. (2021). Antifungal effects of plant extracts on *Colletotrichum gloeosporioides* in chilli pepper (*Capsicum frutescens* L.). Journal of Tropical Plant Protection, 2(2), 68–74. https://doi.org/10.21776/ub.jtpp.2021.002.2.5
[16] Begum, S., & Nath, P. S. (2015). Eco-friendly management of anthracnose of chilli caused by Colletotrichum capsici. Journal of Applied and Natural Science, 7(1), 119–123. https://doi.org/10.31018/jans.v7i1.574
[17] Hodiyah, I., Natawijaya, D., Hartini, E., Setiawan, W., & Meylani, V. (2023). The effectiveness of botanical pesticides as antifungal on chili (*Capsicum annuum* L.) disease. International Journal of Design & Nature and Ecodynamics, 18(1), 183–188. https://doi.org/10.18280/ijdne.180122
[18] Zhong, J., Bai, X. Y., Zhang, Z., Li, X. G., & Zhu, J. Z. (2025). Biocontrol potential of *Streptomyces lactacystinicus* producing volatile organic compounds against postharvest anthracnose of chili pepper. Postharvest Biology and Technology, 230, 113758. https://doi.org/10.1016/j.postharvbio.2025.113758
[19] Kumar, A., Rabha, J., & Jha, D. K. (2021). Antagonistic activity of lipopeptide-biosurfactant producing *Bacillus subtilis* AKP against Colletotrichum capsici. Biocatalysis and Agricultural Biotechnology, 36, 102133. https://doi.org/10.1016/j.bcab.2021.102133
[20] Qiao, J., Zhang, R., Liu, Y., & Liu, Y. (2023). Evaluation of the biocontrol efficiency of *Bacillus subtilis* wettable powder on pepper root rot caused by Fusarium solani. Pathogens, 12(2). https://doi.org/10.3390/pathogens12020225
[21] Suprapta, D. N. (2022). Biocontrol of anthracnose disease on chili pepper using a formulation containing *Paenibacillus polymyxa* C1. Frontiers in Sustainable Food Systems, 5, 1–7. https://doi.org/10.3389/fsufs.2021.782425
[22] Kim, S. H., Lee, Y., Balaraju, K., & Jeon, Y. (2023). Evaluation of *Trichoderma atroviride* and *Trichoderma longibrachiatum* as biocontrol agents in controlling red pepper anthracnose in Korea. Frontiers in Plant Science, 14, 1–15. https://doi.org/10.3389/fpls.2023.1201875
[23] Liotti, R. G., da Silva Figueiredo, M. I., & Soares, M. A. (2019). *Streptomyces griseocarneus* R132 controls phytopathogens and promotes the growth of pepper (*Capsicum annuum*). Biological Control, 138, 104065. https://doi.org/10.1016/j.biocontrol.2019.104065
[24] Sutarman, Setiorini, T., Li'aini, A. S., Purnomo, & Rahmat, A. (2022). Evaluation of *Trichoderma asperellum* effect toward anthracnose pathogen activity on red chili (*Capsicum annuum* L.) as an eco-friendly pesticide. International Journal of Environmental Science and Development, 13(4), 131–137. https://doi.org/10.18178/ijesd.2022.13.4.1383
[25] Paradisa, Y. B., Wahyuni, Mulyaningsih, E. S., Perdani, A. Y., & Prianto, A. H. (2021). Evaluation of plant-based pesticide containing neem extract (*Azadirachta* sp.) to control anthracnose growth in chili fruits. Jurnal Fitopatologi Indonesia, 16(3), 112–122. https://doi.org/10.14692/jfi.16.3.112-122
[26] Rony, M. A. R., Hosen, S., & Bashar, M. (2021). Efficacy of chemical fungicides and plant extracts against anthracnose pathogens of Capsicum frutescens L. Bangladesh Journal of Botany, 50(2), 437–440. https://doi.org/10.3329/BJB.V50I2.54104
[27] Sukdee, S. (2023). Antifungal activity of plant extracts against *Colletotrichum capsici* causal agent of chili anthracnose. Rattana Journal of Science and Technology, 5(1), 1–8.
[28] Ibrahim, N. F., Yin, W. K. A. H., Saleh, N. U. R. H., Ahmad, F. T., & Lob, S. (2020). *Colletotrichum* species in harvested chili. [Journal], 49, 241–246.
[29] Köhl, J., Kolnaar, R., & Ravensberg, W. J. (2019). Mode of action of microbial biological control agents against plant diseases: Relevance beyond efficacy. Frontiers in Plant Science, 10, 1–19. https://doi.org/10.3389/fpls.2019.00845
[30] Costa, L. T. M., Smagghe, G., Viteri Jumbo, L. O., Santos, G. R., Aguiar, R. W. S., & Oliveira, E. E. (2025). Selective actions of plant-based biorational insecticides: Molecular mechanisms and reduced risks to non-target organisms. Current Opinion in Environmental Science & Health, 44, 100601. https://doi.org/10.1016/j.coesh.2025.100601
[31] Gupta, I., Singh, R., Muthusamy, S., Sharma, M., Grewal, K., Harminder Pal Singh, H. P., & Batish, D. R. (2023). Plant essential oils as biopesticides: Applications, mechanisms, innovations, and constraints. Plants, 12(16), 1–29. https://doi.org/10.3390/plants12162916
[32] Zhao, A., Sun, J., & Liu, Y. (2023). Understanding bacterial biofilms: From definition to treatment strategies. Frontiers in Cellular and Infection Microbiology, 13, 1–23. https://doi.org/10.3389/fcimb.2023.1137947
[33] Bartal, A., Huynh, T., Kecskeméti, A., Vörös, M., Kedves, O.,Varga, M., Kredics, L., Vágvölgyi, C., Szekeres, A, & Allaga, H. (2023). Identification of surfactin-type biosurfactants produced by

Bacillus species isolated from the rhizosphere of vegetables. Molecules, 28(3), 1–15. https://doi.org/10.3390/molecules28031172

[34] Singh, S., Singh, A.K., Pradhan, B., Tripathi, S., Kumar, K.S., Chand, S., Prangya Ranjan Rout, P.R., Shahid, M.K.(2024). Harnessing *Trichoderma* mycoparasitism as a tool in the management of soil-dwelling plant pathogens. Microbial Ecology, 87(1). https://doi.org/10.1007/s00248-024-02472-2

[35] Elhamouly, N. A., Hewedy, O.A., Zaitoon, A., Miraples, A., Elshorbagy, O.T., Hussien, S., Tahan, A.E., & Peng, D. (2022). The hidden power of secondary metabolites in plant–fungi interactions and sustainable phytoremediation. Frontiers in Plant Science, 13, 1–21. https://doi.org/10.3389/fpls.2022.1044896

[36] Jisha, M. S., Linu, M. S., & Sreekumar, J. (2018). Induction of systemic resistance in chilli (*Capsicum annuum* L.) by *Pseudomonas aeruginosa* against anthracnose pathogen *Colletotrichum capsici*. Journal of Tropical Agriculture, 56(2), 153–166.

[37] Madlhophe, S., Ogugua, U. V., Makhubu, F. N., & Figlan, S. (2025). Use of biological control agents for managing fungal pathogens in Solanaceae crops: Progress and future perspectives. Discover Applied Sciences, 7(1). https://doi.org/10.1007/s42452-025-06500-9

[38] Tyagi, A., Tamang, T.L., Kashtoh, H., Mir, R.A., Mir, Z.A., Manzoor, S., Manzar, N., Gani, G., Vishwakarma, S.K., Almalki, M.A., & Ali, S. (2024). A review on biocontrol agents as a sustainable approach for crop disease management: Applications, production, and future perspectives. Horticulturae, 10(8). https://doi.org/10.3390/horticulturae10080805