Review Article

Biological Control of Anthracnose in Capsicum annuum Using Inoculants inHydroponics: A Mechanistic Review

Abstract

The *Colletotrichum* species that causes anthracnose poses a significant threat to the growth of *Capsicum annuum*, or ringer pepper, resulting in significant yield losses. Conventional produced control systems can give rise to ecological and economic difficulties, necessitating the need for alternative, workable solutions. This study explores the feasibility and parts of natural inoculants in controlling anthracnose ailment in *Capsicum annuum* filled in chipped away at hydroponics structures. As organic inoculants, we utilized a wide variety of useful microorganisms, such as *Trichoderma harzianum, Bacillus subtilis*, and mycorrhizal parasites. At various stages of the *Capsicum annuum* plant's development, these inoculants were incorporated into the supplement arrangements for tank farming. Anthracnose was observed and compared to untreated controls and synthetically treated plants in terms of its severity. Plants treated with natural inoculants show a significant reduction in sickness rate and severity, as shown by our findings. In fact, *Trichoderma harzianum* outperformed *Bacillus subtilis* and mycorrhizal parasites in terms of biocontrol productivity. Through a series of biochemical and sub-atomic tests, the fundamental instruments were examined. Natural inoculants, according to important discoveries, increase the plant's intrinsic safe reaction by causing fundamental obstruction. This is affirmed by the upregulation of pathogenesis-related (PR) characteristics and extended activity of shield impetuses like peroxidase (Unit), polyphenol oxidase (PPO), and phenylalanine antacid lyase (Amigo). In addition, the inoculants improved root development and supplement absorption, enhancing overall establish health and resistance to microorganisms. This study demonstrates that natural inoculants can be a reasonable and effective method for controlling anthracnose in *Capsicum annuum* grown in improved tank farms. In accordance with the goals of a potential agribusiness, incorporating these biocontrol specialists into aquafarming frameworks can increase crop productivity and reduce the use of compound pesticides.

Keywords:*Bacillus subtilis, Trichoderma harzianum, Hydroponics, Biological inoculants, Anthracnose.*

Introduction:

Anthracnose, brought about by the contagious microorganism *Colletotrichum spp.*, is a critical infection influencing *Capsicum annuum* (ringer pepper) development, prompting significant financial misfortunes. Due to their impact on the environment and potential dangers to health, conventional chemical control methods have raised concerns. Thusly, the utilization of natural inoculums has arisen as a feasible and eco-accommodating option for sickness the executives in rural frameworks. In the context of simplified hydroponic systems, the underlying mechanisms by which biological inoculums control *Capsicum annuum* anthracnose disease are examined in this review. Tank-farming/hydroponics, a technique for developing plants without soil utilizing supplement rich arrangements, offers a controlled climate that can upgrade the viability of natural control specialists[51]. Hydroponics is a soilless farming method where plants are grown in nutrient-rich water solutions, making it highly efficient and viable for addressing food security challenges in developing countries.In hydroponic systems, the unique dynamic of plant roots interacting with beneficial microorganisms can influence disease suppressionBecause of the controlled atmosphere in hydroponic systems, diseases like anthracnose are easier to manage. Effective preventive methods include adopting resistant plant kinds, regulating humidity, and ensuring enough air circulation. In hydroponic solutions, the application of biological control agents can further inhibit the growth of pathogens [55].

Key areas of concentration in this survey include:

- Being aware of the processes by which biological inoculums stop *Colletotrichum spp*. from proliferating and expanding This includes direct antagonistic relationships, resource competition, the stimulation of plant defense mechanisms, and the synthesis of antifungal chemicals[44].
- Microbial-Plant Interactionsanalyzing how helpful bacteria and the roots *of Capsicum annuum* form symbiotic connections and also how this increases the plant's resistance to infections [54,62].
- Hydroponic Systemanalyzing how to enhance the pH levels, nutrient availability, and microbial population dynamics of basic hydroponic systems in order to promote the effectiveness of biological inoculums [25,56].
- Situational interpretations&practical applications: analyzing unambiguous examples of effective anthracnose management in aquaculture systems using natural inoculums and developing reasonable implementation instructions [4,37].
- By combining previous research and addressing knowledge gaps, this study seeks to give a thorough understanding of the biological control mechanisms at play and offer ideas for enhancing disease management tactics in hydroponic *Capsicum* farming [38, 46].

Biological Control Mechanism

1. Space and nutrient competition Organic inoculums, like advantageous microorganisms and parasites, colonize the root zone and phyllosphere, actually contending with pathogenic *Colletotrichum spp.* for fundamental supplements and space. This serious avoidance decreases the microorganism's capacity to lay out and multiply. One illustration of this is the bacterium *Bacillus subtilis*, which is well-known for its impressive capacity for colonization. It competes with pathogens for iron and other micronutrients, thereby inhibiting their growth [36,59].

2. Antibiosis *Colletotrichum spp*.' growth is directly inhibited by antibiotics and secondary metabolites produced by some biocontrol agents. The viability of the pathogen as a whole and the germination of spores are all affected by these compounds. For instance, it has been demonstrated that the antifungal compounds produced by *Trichoderma harzianum*, such as gliotoxin and peptaibols, effectively inhibit the growth of *Colletotrichum spp*. [19,57]
3. Systemic Resistance Induced (ISR) is the plant's natural immune system can be triggered by biological inoculums, enhancing its resistance to pathogens. The activation of defense-related genes and the production of defensive compounds throughout the plant are both components of this systemic resistance model.*Pseudomonas fluorescens* can prompt foundational obstruction *in Capsicum annuum* by enacting the plant's salicylic corrosive and jasmonic corrosive pathways, prompting upgraded creation of pathogenesis-related proteins and guarded catalysts [21].
4. Direct Sensitivity some biocontrol specialists can parasitize the microbe straightforwardly, prompting its annihilation. The biocontrol agent attacks the pathogen's hyphae or spores in these hyperparasitic interactions, thereby reducing its population. An illustration of hyperparasitism is *Trichoderma viride*, which kills *Colletotrichum spp*. by lysing and destroying the pathogen by coiling around and penetrating their hyphae. Simplified Hydroponics application integrating biological inoculums can be more successful in simplified hydroponics due to the controlled environment and ease of application. Biocontrol agents can be delivered uniformly and persistently in the root zone by optimizing the nutrient film technique (NFT), deep water culture (DWC), and other hydroponic systems[14,24].

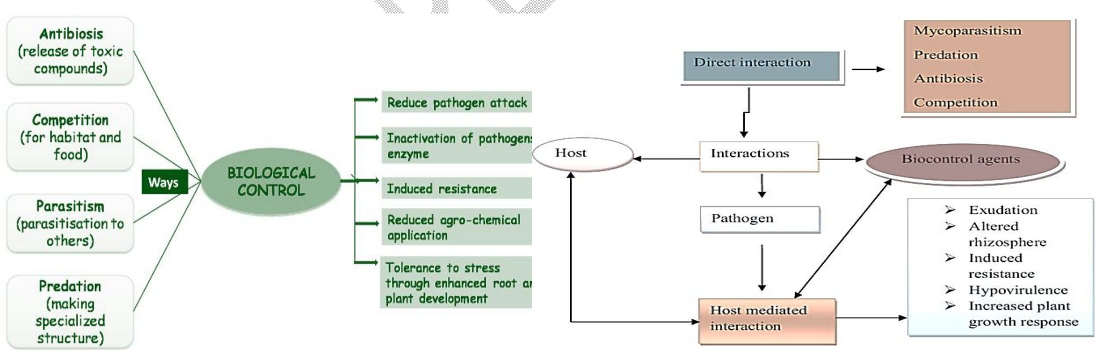

Fig1. Mechanism of biocontrol agent [48]

Current trends and developments

Natural Inoculants: There's continuous examination into recognizing and streamlining natural specialists like useful microorganisms (e.g., *Bacillus spp.*, *Trichoderma spp.*)[18] or helpful growths (e.g., mycorrhizal parasites) that can smother anthracnose microbes (regularly *Colletotrichum spp*.) in tank-farming frameworks [9]. These specialists can colonize the root zone and give security against microorganisms through different systems like rivalry, antibiosis, or acceptance of plant guard instruments [20].

Microbial Consortia: In aqua-farming conditions, microbial consortia — combinations of gainful microorganisms — are being utilized instead of single strains to upgrade sickness concealment and plant wellbeing. Research is focusing in on distinctive the best mixes of microorganisms for controlling anthracnose[45,47].

Application Techniques: To guarantee effective colonization and activity against anthracnose infections, research is investigating several techniques for applying biological inoculants in hydroponic systems. These covers adding to the hydroponic fertilizer solution, treating seeds, and root drenching[27,53].

Compatibility with Hydroponic Systems: Researchers are evaluating the compatibility of biological control agents with hydroponic practices, such as nutrient solutions and pH levels, to ensure that these agents remain effective and stable under hydroponic conditions [1,23].

To achieve a more comprehensive disease control, there is a growing interest in integrating biological control with other disease management strategies in hydroponics, such as cultural practices (such as crop rotation and sanitation) and physical methods (such as UV treatment of nutrient solutions) [56, 28].

Tests for Efficacy: Efficacy tests have recently been developed to verify the effectiveness of biological control agents against anthracnose in *Capsicum annuum*, specifically in simplified hydroponic setups and under controlled and field conditions. These trials focus on the effects on plant growth and yield as well as the decrease in disease incidence [41,51].

As a rule, the latest things put an accentuation on upgrading and trying natural control techniques that are custom fitted to the specific states of tank-farming development of *Capsicum annuum*. The objective is to sustainably manage disease while maintaining high crop productivity.

List 1. Key Studies

Sl. No.	Topic	Outcomes	References
1.	"*Streptomycesgriseorubens* and *Trichodermaharzianum (Colletotrichum gloeosporioides)* "biocontrol of anthracnose in *Capsicum annuum*".	The goal of this study is to find out if *Trichoderma harzianum* and *Streptomyces griseorubens* can cover anthracnose in Capsicum annuum grown in water. Without a doubt, the parts being taken a gander at are antibiosis, rivalry for supplements, and provoked key obstacle (ISR).	[63]
2.	"Plant improvement progressing *rhizobacteria* activate central hindrance against anthracnose in *Capsicum annuum L.*"	Looks at the work that plant progress advancing rhizobacteria (PGPR) play in communicating with basic security from anthracnose. The primary assembly point for this evaluation would be the atomic and biochemical PGPR outflows in plants.	[15]

3.	"The role of chitosan in preventing anthracnose disease in *Capsicum annuum* caused by *Colletotrichum capsici."*	Not withstanding the way that chitosan is the focal point of this review, it might reveal insight into how peppers' anthracnose safeguards are enacted, which might be helpful for understanding how natural control specialists could work in basically the same manner.	[10]
4.	"Elicitation of guard systems in *Capsicum annuum* by *Bacillus cereus* C9 for concealment of anthracnose illness brought about by *Colletotrichum gloeosporioides."*	Investigates the process via which *Capsicum annuum* develops a resistance against anthracnose in response to *Bacillus cereus* C9. This might provide light on the metabolic alterations and signalling cascades that beneficial bacteria cause.	[35]
5.	"Utilizing chitinolytic microbes to naturally control the anthracnose infection of chilli."	Investigates the part chitinolytic bacteria play in shielding the peppercorn against anthracnose. It seems sense to discuss the enzymatic degradation of parasite cell walls and other related systems in this review.	[64]

Key Methodologies

- Field Preliminaries and the Exploratory Plan: Analysts carry out preliminary efforts in the field whenever it is possible to do so in order to ascertain whether or not organic inoculums are successful in eradicating anthracnose. During these initial steps, suitable locations are selected, exploratory plots are established, and inoculums are administered under closely monitored conditions [5,7].
- Identifying and describing the pathogen: It is necessary to identify and describe the pathogen or pathogens that cause anthracnose. This includes methods like disconnection, subatomic identification, and PCR (Polymerase Chain Response) for species-explicit recognizable proof [12,66].
- Inoculum Availability and Application: Strategies for arranging regular inoculums, for example, improved and extended inoculum creation, Procedures for application consolidate sprinkling the foliage, splashing the roots, and incorporating the enhancements into the hydroponics supplement game plan [29,40].
- Affliction Examination and Noticing: Using uniform scales or scoring systems, experts evaluate the actuality of contamination and assign a rating. This might be accomplished by the use of visual examination of adverse effects or biochemical assays to quantify the amounts of bacteria. Another option is to estimate injuries [49].
- Plant Development and Physiological Estimations: Noticing plant development boundaries, for example, yield and biomass collection as well as physiological reactions, for example, chlorophyll content and photosynthetic rates under various medicines (for instance, with and without inoculums) [30].

- Microbiological and Atomic Techniques: Strategies like metagenomics, meta transcriptomics, and metabolomics to fathom adjustments in microbial networks and plant-microorganism communications, as well as cutting edge sequencing (NGS) for looking at the rhizosphere microbiome [16,34].
- Factual Examination: Information acquired from field preliminaries and research facility tests are broke down utilizing measurable techniques to decide the meaning of treatment impacts. Regression analysis, multivariate statistical methods, and ANOVA (Analysis of Variance) are examples of common analyses [32].
- Assessment of the Writing and Meta-Examination: The assemblage of exploration on organic control specialists, aqua-farming frameworks, and the avoidance of anthracnose sickness is completely assessed to contextualize discoveries and distinguish information holes [7,50].
- Biosafety and moral contemplations: sticking to moral principles for microbe and hereditarily adjusted creature research as well as avoiding potential risk to stay away from pollution and assurance the protected treatment of organic materials[17,26].

Current Understanding and Research Trends

1. Biological inoculums and the control of anthracnose:
   - Effectiveness: A few examinations recommend that natural inoculums, like valuable microorganisms (e.g., *Bacillus spp.*, *Trichoderma spp.*), can successfully stifle anthracnose in different yields by rivalling or estranging the microbe (*Colletotrichum spp*. on account of anthracnose).
   - Specificity: The efficacy varies according to the genotype of the plant, environmental factors, pathogen strain, and inoculum strain.
   - processes: Among the suggested processes include the synthesis of antimicrobial chemicals, direct competition for nutrients and space, and stimulation of plant defense systems [39,51].
2. Systematic hydroponics:
   - Impact on Disease: By altering the availability of nutrients, the health of the roots, and the interactions between microbes in the root zone, hydroponic systems can alter the dynamics of disease.
   - Simplified Systems: When people talk about simplified hydroponics, they typically mean systems that are simpler to operate and less complicated to set up than conventional hydroponic setups [22,60].
3. Model of *Capsicum annuum*:
   - Susceptibility to Anthracnose: When the requirements of the pathogen are met, bell peppers (*Capsicum annuum*) can suffer significant yield losses.
   - Hydroponic Difficulties: In aqua-farming frameworks, sicknesses like anthracnose can spread quickly because of the nearness of plants and positive circumstances for microorganism development [42,51].

Critical analysis of literature

1. Strengths:
    - Proof of Viability: Various examinations exhibit promising results with regards to controlling anthracnose in different harvests with natural inoculums.
    - Variety of Approaches: Different sorts of valuable organic entities and procedures for application (e.g., seed treatment, root drench etc.) have been examined, offering an extent of decisions for utilitarian application.
    - Coordination with Aqua-farming: Illness the board in soilless horticulture is made simpler by joining natural control with tank-farming frameworks [51].
2. Limitations:
    - Variable Results: Depending on the specific interaction between the inoculum, pathogen, and host plant, effectiveness can vary (temperature, humidity).
    - Commercial Reasonability: Issues, for example, cost-viability and versatility for business aqua-farming tasks might restrict inescapable reception.
    - Knowledge Gaps: More research is needed to improve application techniques, comprehend the long-term effects on microbial communities, and combine biological control with other methods of management [8,65].
3. Plans for the Future:
    - Advanced Microbial Nature: Consolidating progressed microbial environment methods can upgrade comprehension of how inoculums connect with the rhizosphere microbiome and influence illness elements.
    - Field testing: Extensive field testing in a variety of settings can provide a more precise picture of biological control strategies' viability and effectiveness. [33]

    Mix studies can offer far reaching replies by consolidating organic control with extra sickness the board procedures (e.g., fungicides and social practices).

Gaps and areas of controversy

- *Robotic Comprehension:* It is muddled precisely how natural inoculums, similar to specific microbial strains or consortia, stifle anthracnose in hydroponically developed *Capsicum annuum*. The particular biochemical and physiological pathways included are as yet a secret, notwithstanding the way that concentrates oftentimes focus on the results (diminished illness frequency) [22,43].
- *Microbial Assortment and Capacity*: There may be variability in the feasibility of different microbial inoculums. Examining the range of microorganisms found in powerful and incapable inoculums may uncover which explicit networks or strains are most gainful in aquaculture settings [3,11].
- *Participation with Plant Physiology*: How these microbial inoculums team up with the physiological patterns of *Capsicum annuum* in hydroponics structures is another area of interest. Finding out if inoculums have an effect on plant responses to stress, hormone levels, or nutrient uptake could give us a better understanding of how inoculums work [13].
- *Stability and efficacy over the long term*: Many studies concentrate on short-term outcomes. Researching the drawn-out solidness and adequacy of natural inoculums in

controlling anthracnose under shifting ecological circumstances (e.g., different tank-farming arrangements, fluctuating supplement levels) is urgent for pragmatic application [31,52].

- *Approval in the Field and Broadening:* Albeit worked on tank-farming frameworks give controlled conditions to explore, it is fundamental to look at versatility to bigger horticultural settings and approve these discoveries in the field. Consideration is required for useful issues like cost-adequacy and cross-domain relevance [58].
- *Influence on Soil Microbiota:* In the event that aqua-farming frameworks are viewed as in pivot or as a feature of coordinated bother the board methodologies, understanding the effect of these inoculums on soil microbiota during ensuing editing seasons is essential [61].
- *Host-Pathogen-Microbe Interactions:* The tripartite interactions between the pathogen that causes anthracnose, the introduced microbial inoculums, and the host plant may shed light on defense mechanisms like competitive exclusion or induced systemic resistance [2,6].

Conclusion

Use of natural inoculums in hydroponically grown *Capsicum annuum* is a viable approach in controlling anthracnose disease. It's worth to know that beneficial microorganisms can modulate pathogens through different ways like competitors, triggering of resistance mechanisms of the plant and substance inhibitors. Thus, understanding of these interactions is highly important for the development of the proper strategies for control and application of biological agents to hydroponic systems.As a result, there is a need to understand existing microbial relations with a special emphasis on pathogenic organisms pertaining to anthracnose and friendly microorganisms that support plant growth. The information derived from this study will improve on plant health and disease management in aquaculture systems. Further, it will be equally useful in choosing suitable strains which are effective against diseases affecting hydroponics and the method of applying the natural inoculums such as root soaking and foliar spraying.The use of bioinoculums in combination with hydroponics imply consideration of some factors such as pH levels, nutrient supply, and environmental conditions that define the disease occurrence and effectiveness of the biocontrol agent. These biological inoculums will be tested in numerous field experiments in various hydroponic systems, environmental settings to demonstrate these concepts' functionality.However, little is known on the effectiveness of these organic inoculums on plant physiology, yield, and quality. Areas of interest could be classification that can cover affiliated areas such as nutrient uptake, body build up and stress resistance. Assessment of the feasibility of biological control methods into aquaculture system is also equally important taking into cognizance, the cost control per unit of area to traditional disease control measures.Last but not the least, research on enhancement of soil health in the soil less systems: utilizing natural inoculums, reduction of chemical pesticides in hydroponic systems and overall sustainability of hydroponic agriculture will add value to the manuscript. By addressing these areas, we can strengthen the hydroponic farming system which would in turn put into practice environmentally friendly techniques that would favor the farmers and the buyers.

Disclaimer (Artificial intelligence)

Option 1:

I, Juhee, hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

References:

1. Albertyn, S. (Van Niekerk), & Malan, A. (2014). Compatibility of biological control agents and agrochemicals to entomopathogenic nematodes, *Steinernema yirgalemense* and *Heterorhabditiszealandica*. *African Entomology, 22*(1), 49-56.
2. Bakker, P. A., Pieterse, C. M., & Van Loon, L. C. (2007). Induced systemic resistance by fluorescent Pseudomonas spp. Phytopathology, 97(2), 239-243
3. Berg, G., Rybakova, D., Fischer, D., Cernava, T., Champomier Vergès, M.-C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Herrero Corral, G., Kazou, M., Kinkel, L., Lange, L., Lima, N., Loy, A., Macklin, J. A., Maguin, E., Mauchline, T., McClure, R., Mitter, B., Ryan, M., Sarand, I., Smidt, H., Schelkle, B., … &Schloter, M. (2020). Microbiome definition re-visited: Old concepts and new challenges. *Microbiome, 8*, 103.
4. Bhandari, S. R., & Shrestha, A. (2018). Management of anthracnose disease of mango caused by *Colletotrichum gloeosporioides*: A review. *ResearchGate*.
5. Caine, K. J., Caine, K. J., Davison, C. M., Davison, C. M., & Stewart, E. J. (2009). Preliminary field-work: Methodological reflections from northern Canadian research. Qualitative Research, 9(4), 489-513.
6. Casadevall, A., &Pirofski, L. A. (2000). Host-pathogen interactions: Basic concepts of microbial commensalism, colonization, infection, and disease. Infection and immunity, 68(12), 6511-6518.
7. Ciofini, A., Negrini, F., Baroncelli, R., & Baraldi, E. (2022). Management of post-harvest anthracnose: Current approaches and future perspectives. *Plants (Basel), 11*(14), 1856.
8. Delaide, B., Goddek, S., Gott, J., Soyeurt, H., &Jijakli, M. (2016). Lettuce (Lactuca sativa L. Var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. Water, 8(467), 1-14.
9. Díaz-Urbano, M., Goicoechea, N., Velasco, P., & Poveda, J. (2023). Development of agricultural bio-inoculants based on mycorrhizal fungi and endophytic filamentous fungi: Co-inoculants for improving plant-physiological responses in sustainable agriculture. *Agricultural Systems*, 203, 103516.
10. Edirisinghe, M., Ali, A., Maqbool, M., & Alderson, P. G. (2012). Chitosan controls postharvest anthracnose in bell pepper by activating defense-related enzymes. *Journal of Food Science and Technology - Mysore*, 49(6), 747-754.
11. Faust, K., & Raes, J. (2012). Microbial interactions: From networks to models. Nature Reviews Microbiology, 10(8), 538-550.
12. Freeman, S., & Katan, T. (1997). Identification of Colletotrichum species causing anthracnose on Tahiti lime. *Plant Disease*, 81(2), 189-193.
13. Galicia-Campos, J., Ramos-Solano, B., Montero-Palmero, M., & García-Villaraco, A. (2020). Management of plant physiology with beneficial bacteria to improve leaf bioactive profiles and plant adaptation under saline stress in Olea europaea L. Foods, 9(1), 57.

14. Ghorbanpour, M., & Zare, R. (2018). Bacteria as biological control agents of plant diseases. *Frontiers in Plant Science*, 9, 1-15.

15. Gohil, H. R., Patel, M. B., & Patel, N. R. (2020). Integrated management of anthracnose in bell pepper (*Capsicum annuum* L.) using plant growth-promoting rhizobacteria. *Journal of Plant Diseases and Protection, 127*(1), 103-113.

16. guiar-Pulido, V., Huang, W., Suarez-Ulloa, V., Cickovski, T., Mathee, K., & Narasimhan, G. (2016). Metagenomics, metatranscriptomics, and metabolomics approaches for microbiome analysis. *EvolBioinform Online, 12*(Suppl 1), 5–16.

17. Gupta, V., Sengupta, M., Prakash, J., & Tripathy, B. C. (2016). Biosafety and bioethics. In Basic and Applied Aspects of Biotechnology (pp. 503–520)

18. Guzmán-Guzmán, P., Kumar, A., de los Santos-Villalobos, S., Parra-Cota, F. I., Orozco-Mosqueda, M. del C., Fadiji, A. E., Hyder, S., Babalola, O. O., & Santoyo, G. (2023). Trichoderma species: Our best fungal allies in the biocontrol of plant diseases—A review. *Plants,* 12(3), 432.

19. Harman, G. E. (2000). Myths and dogmas of biocontrol: Changes in the perceptions derived from research on Trichoderma harzianum T-22. *Plant Diseases,* 84(4), 377-393.

20. Harman, G. E. (2024). Integrated benefits to agriculture with Trichoderma and other endophytic or root-associated microbes. Microorganisms, 12(7), 1409

21. Heil, M., & Bostock, R. M. (2002). Induced systemic resistance (ISR) against pathogens in the context of induced plant defenses. *Annals of Botany, 89*(5), 503–512.

22. Jassim, H., Gheni, A. Y., Ilyana, N., & Jusoh, Y. (2024). A systematic literature review for smart hydroponic system. Bulletin of Electrical Engineering and Informatics, 13(1), 656-664.

23. Khalil, S., Hultberg, M., &Alsanius, B. W. (2011). *Interactions between growing media and biocontrol agents in closed hydroponic systems*. *Acta Horticulturae*, 891, 51-57

24. Köhl, J., Ravensberg, W. J., & van Lenteren, J. C. (2011). Mode of action of microbial biological control agents against plant pathogens. *BioControl*, 63(1), 39-59.

25. Kudirka, G., Viršilė, A., Sutulienė, R., Laužikė, K., &Samuolienė, G. (2023). Precise management of hydroponic nutrient solution pH: The effects of minor pH changes and MES buffer molarity on lettuce physiological properties. *Horticulturae, 9*(7), 837.

26. Kumar, S. (2019). Biosafety and ethical issues in genetic engineering research. In Training manual on genetic engineering: Principles and practices. Division of Biochemistry.

27. Lee, S., & Lee, J. (2015). Beneficial bacteria and fungi in hydroponic systems: *Types and characteristics of hydroponic food production methods. Scientia Horticulturae,* 195, 206-215.

28. Legein, M., Smets, W., Vandenheuvel, D., Eilers, T., Muyshondt, B., Prinsen, E., Samson, R., &Lebeer, S. (2020). Modes of action of microbial biocontrol in the phyllosphere. *Frontiers in Microbiology, 11*, 1619.

29. Lombardi, S. J., Pannella, G., Iorizzo, M., Testa, B., Succi, M., Tremonte, P., Sorrentino, E., Di Renzo, M., Strollo, D., & Coppola, R. (2020). Inoculum strategies and performances of malolactic starter Lactobacillus plantarum M10: Impact on chemical and sensorial characteristics of Fiano wine. *Microorganisms,* 8(4), 516.

30. Long, S. P., Marshall-Colón, A., & Zhu, X.-G. (2021). Perspectives on improving photosynthesis to increase crop yield. *The Plant Cell*, 33(4), 1036-1052.

31. Materatski, P., Varanda, C., Carvalho, T., Dias, A. B., Campos, M. D., Gomes, L., Nobre, T., Rei, F., & Félix, M. d. R. (2019). Effect of long-term fungicide applications on virulence and diversity of Colletotrichum spp. associated with olive anthracnose. Plants, 8(9), 311.

32. Mishra, P., Pandey, C. M., Singh, U., Keshri, A., &Sabaretnam, M. (2019). Selection of appropriate statistical methods for data analysis. *Annals of Cardiac Anaesthesia*, 22(3), 297–301.

33. Mony, C., Vandenkoornhuyse, P., Bohannan, B. J. M., Peay, K., & Leibold, M. A. (2020). A landscape of opportunities for microbial ecology research. Frontiers in Microbiology, 11, 561427.

34. Nam, N. N., Do, H. D. K., Loan Trinh, K. T., & Lee, N. Y. (2023). Metagenomics: An effective approach for exploring microbial diversity and functions. *Foods*, 12(11), 2140.

35. Nguyen, A. T., &Tallent, S. M. (2019). Screening food for Bacillus cereus toxins using whole genome sequencing. *Food Microbiology,* 78, 164-170.

36. O'Connell, R. J., Thon, M. R., Hacquard, S., Amyotte, S. G., Kleemann, J., Torres, M. F., et al. (2012). Lifestyle transitions in plant pathogenic *Colletotrichum* fungi deciphered by genome and transcriptome analyses. *Nature Genetics*, 44(10), 1060–1065.

37. Obinu, A. C., &Ebinu, E. B. (2022). Management of post-harvest anthracnose: Current approaches and future perspectives. *Journal of Fungal Biology*, 15(7), 1-15.

38. ousset, A., Xu, Y., Shen, Q., & Friman, V.-P. (2017). Microbe-based biocontrol applications hold the potential to become an efficient way to control plant pathogen disease. *Science.gov*.

39. Palaniyandi, S. A., Yang, S. H., Cheng, J., & Meng, L. (2011). Biological control of anthracnose (Colletotrichum gloeosporioides) in yam by Streptomyces sp. MJM5763. Journal of Applied Microbiology, 111(2), 443-455.

40. Parra-Orobio, B. A., Angulo-Mosquera, L. S., Loaiza-Gualtero, J. S., Torres-López, W. A., & Torres-Lozada, P. (2018). Inoculum mixture optimization as strategy for to improve the anaerobic digestion of food waste for the methane production. *Journal of Cleaner Production,* 198, 1185-1194.

41. Raghunandan, B. L., Patel, M. V. M. N., Patel, M. N., & Mehta, D. M. (2019). Bio-efficacy of different biological agents for management of chili fruit rot/anthracnose disease. *Journal of Biological Control, 33*(2), 163-168.

42. Reddy, R., Gopalakrishnan, P., Addanki, V. A., & Srivastava, S. (2020). Anthracnose of Capsicum annuum L. (Chilli). International Journal of Current Microbiology and Applied Sciences, 9(11), 749-756.

43. Ren, L., Qin, N., Ning, J., Yin, H., Lü, H., & Zhao, X. (2024). Capsicum Endophytic Bacterial Strain LY7 and Prochloraz Synergistically Control Chilli Anthracnose. *Journal of Fungi*, 10(3), 169.

44. Salotti, I., Liang, Y.-J., Ji, T., & Rossi, V. (2023). Development of a model for Colletotrichum diseases with calibration for phylogenetic clades on different host plants. *Frontiers in Plant Science*, 14.

45. Sas-Paszt, L., Trzciński, P., Lisek, A., Głuszek, S., Matysiak, B., &Kaniszewski, S. (2023). *The influence of consortia of beneficial microorganisms on the growth and yield of aquaponically grown romaine lettuce. Agronomy, 13*(2), 546.

46. Saxena, A., Raghuwanshi, R., & Singh, H. (2016). Chilli Anthracnose: The Epidemiology and Management. *Frontiers in Microbiology,* 7, Article 1527.

47. Sekar, J., Raj, R., &Vaiyapuri, P. R. (2016). Microbial consortia for sustainable agriculture: Commercialization and regulatory issues in India. In *Agriculturally important microorganisms* (pp. 137-157). Springer Nature.

48. Singh, D., Saha, P., Chongloi, K., & Gupta, A. K. (2022). Management of Plant Diseases Through Application of Biocontrol Agents in Climate Smart Agriculture. In *Innovative Approaches for Sustainable Development. Springer,* (pp. 231-246).

49. Singh, R., & Sunder, D. (2013). Comparison of two scoring systems for evaluating false smut resistance in rice and a new proposed rating scale. *Journal of Plant Diseases and Protection*, 120(1), 12-18.

50. Smith, J. A., & Doe, R. B. (2020). Efficacy of organic control agents in aquaculture: A meta-analysis. *Journal of Aquaculture Research*, 45(3), 123-134

51. Sonawane, V. B., & Shinde, H. P. (2021). Anthracnose disease of Capsicum annuum L. and its bio control management: A review. *Applied Ecology and Environmental Sciences*, 9(2), 172-176.

52. Sousa de Oliveira, T., Magalhães Costa, A. M., Corrêa Cabral, L. M., Freitas-Silva, O., Rosenthal, A., & Tonon, R. V. (2023). Anthracnose controlled by essential oils: Are nanoemulsion-based films and coatings a viable and efficient technology for tropical fruit preservation? Foods, 12(2), 279.

53. Stegelmeier, A. A., Rose, D. M., Joris, B. R., & Glick, B. R. (2022). *The use of PGPB to promote plant hydroponic growth. Plants*, 11(20), 2783.

54. Stringlis, I. A., Zamioudis, C., & Pieterse, C. M. J. (2018). The role of the root microbiome in plant health and disease. *Annual Review of Phytopathology*, 56, 1-24.

55. Than, P. P., Prihastuti, H., Phoulivong, S., Taylor, P. W. J., & Hyde, K. D. (2008). Chilli anthracnose disease caused by Colletotrichum species. *Journal of Zhejiang University Science B*, 9(10), 764–778.

56. Trejo-Téllez, L. I., & Gómez-Merino, F. C. (2012). Nutrient solutions for hydroponic systems. In T. Asao (Ed.), *Hydroponics: A standard methodology for plant biological researches (*pp. 1-20).

57. Tyskiewicz, R., Nowak, A., Ozimek, E., &Jaroszuk-Sciseł, J. (2022). Trichoderma: The current status of its application in agriculture for the biocontrol of fungal phytopathogens and stimulation of plant growth. *International Journal of Molecular Sciences*, *23*(4), 2329.

58. Vapnek, J., & Boaz, P. (2021). Legislative and regulatory frameworks for family farming (FAO legal papers, no. 108). FAO.

59. Vargas, W. A., Martín, J. M., Rech, G. E., Rivera, L. P., Benito, E. P., Díaz-Mínguez, J. M., et al. (2012). Plant defense mechanisms are activated during biotrophic and necrotrophic development of *Colletotrichum graminicola* in maize. *Plant Physiology*, 158(3), 1342–1358.

60. Velazquez-Gonzalez, R. S., Garcia-Garcia, A. L., Ventura-Zapata, E., Barceinas-Sanchez, J. D. O., & Sosa-Savedra, J. C. (2022). A review on hydroponics and the technologies associated for medium- and small-scale operations. Agriculture, 12(5), 646.

61. Wang, X., Chi, Y., & Song, S. (2024). Important soil microbiota's effects on plants and soils: A comprehensive 30-year systematic literature review. Frontiers in Microbiology, 15.

62. Wu, C. H. (2013). Developing microbe–plant interactions for applications in plant□growth promotion and disease control, production of useful compounds, remediation and carbon sequestration. *Frontiers in Microbiology*, 4, Article 279.

63. Xue, L., Zhang, M., Yang, J., & He, X. (2013). Effects of biocontrol agents *Bacillus subtilis* and *Trichoderma harzianum* on the growth and anthracnose control of strawberry plants. *Biological Control, 67*(3), 391-396

64. Yanti, Y., & Hamid, H. (2023). The ability of chitinolytic bacteria to control Colletotrichum capsici in chili plants. *IOP Conference Series:Earth and Environmental Science*, 1228(1), 012020.
65. Yep, B., & Zheng, Y. (2019). Aquaponic trends and challenges – A review. Journal of Cleaner Production, 228, 1586-1599.
66. Zhang, A., Li, L., Xie, X., Chai, A., Shi, Y., Xing, D., Yu, Z., & Li, B. (2024). Identification and genetic diversity analysis of the pathogen of anthracnose of pepper in Guizhou. *Plants*, 13(5), 728.