Journal of Tea Science Research, 2024, Vol.14, No.4, 192-201
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Feature Review Open Access

Harnessing Beneficial Microbes: Biological Control Strategies for Tea Pests

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Journal of Tea Science Research, 2024, Vol.14, No.4 doi: 10.5376/jtsr.2024.14.0018

Received: 20 May, 2024

Accepted: 28 Jun., 2024

Published: 12 Jul., 2024

Preferred citation for this article:

Zhang X.., Li Y.X., and Zhao Y.C., 2024, Harnessing beneficial microbes: biological control strategies for tea pests, Journal of Tea Science Research, 14(4): 192-201 (doi: 10.5376/jtsr.2024.14.0018)

Abstract Tea cultivation faces serious threats from pests, and traditional chemical pesticides not only harm the environment but also lead to pest resistance. Biological control utilizing beneficial microbes offers a sustainable and eco-friendly solution. This study explores strategies for using beneficial microorganisms such as bacteria, fungi, and viruses to control tea plant pests. It provides a detailed overview of several major beneficial microorganisms and their applications in the pest management of tea plants. The study found that bacteria effectively inhibit pests through antibiosis and microbial antagonism, fungi significantly reduce pest density by inducing systemic resistance and direct parasitism, and viruses provide precise control methods by infecting and killing specific pest species. This study, through practical case studies, demonstrates the successful application of these microbes in tea plantations and discusses the integration of biocontrol with chemical, agricultural, mechanical, genetic, and breeding methods. The research also evaluates the environmental and economic benefits of microbial biocontrol, emphasizing its long-term sustainability and market impact. Despite some challenges and limitations in application, the potential of these microbes will be further realized through technological innovation and scientific research. Future research should focus on advancements in microbial biocontrol technologies and their integration with modern agricultural practices to enhance the sustainability and productivity of tea cultivation.

Keywords Biological control; Beneficial microbes; Tea pests; Sustainable agriculture; Microbial biocontrol

1 Introduction

Tea (*Camellia sinensis*) is one of the most widely consumed beverages globally, but its cultivation faces significant challenges due to various pests. These pests, including mites, tortricid moths, hemipterans, and coleopterans, attack different parts of the tea plant, leading to substantial crop losses annually. The foliage, which is the marketable part of the tea plant, is particularly vulnerable to these pests, necessitating effective management strategies to ensure sustainable production (Nakai and Lacey, 2017).

The traditional reliance on synthetic pesticides for pest control in tea cultivation has led to several adverse effects, including the development of pest resistance, environmental pollution, and pesticide residues in the final product (Deka and Babu, 2021). These issues have driven the agricultural community to seek alternative, eco-friendly pest management strategies. Biological control, which involves the use of natural enemies such as entomopathogenic fungi, bacteria, viruses, and nematodes, has emerged as a promising solution. These microbial agents not only target specific pests but also minimize environmental impact, making them a crucial component of sustainable agriculture (Deka et al., 2022).

This study aims to explore and integrate existing knowledge on the use of beneficial microorganisms as biocontrol agents for tea plant pests. It focuses on evaluating the effectiveness of various microbial agents in controlling tea plant pests and identifying the benefits and limitations of their application in tea cultivation. Additionally, the research provides recommendations for incorporating microbial control into existing pest management practices to enhance the sustainability of tea agriculture. By achieving these goals, the study seeks to promote the development of more sustainable and environmentally friendly pest management practices in tea cultivation, thereby supporting the long-term viability of the tea industry.

2 Types of Beneficial Microbes

2.1 Bacteria as biocontrol agents

Bacteria play a crucial role in the biological control of tea pests. Various bacterial species have been identified as effective biocontrol agents due to their antagonistic properties against plant pathogens and pests. For instance, Bacillus subtilis has been shown to suppress the growth of *Fusarium oxysporum*, a common plant pathogen, through competitive exclusion and production of antimicrobial compounds (Wylie and Punja, 2020). Additionally, bacterial consortia, which combine multiple bacterial strains, have demonstrated enhanced biocontrol efficacy compared to single-strain applications. This approach leverages the diverse modes of action of different bacteria, providing a broader spectrum of pest and disease control (Minchev et al., 2021).

2.2 Fungi and their role in pest control

Fungi are another group of beneficial microbes extensively used in the biological control of tea pests. Entomopathogenic fungi, such as *Metarhizium anisopliae*, have been successfully employed to manage termite populations in tea crops. Field trials have shown that formulations of *M. anisopliae* significantly reduce termite populations without harming beneficial insects or causing phytotoxic effects on tea plants (Deka and Babu, 2021). Additionally, fungi like *Paecilomyces* have been reported to control nematodes and other insect pests, further highlighting their versatility as biocontrol agents (Moreno-Gavíra et al., 2020). The use of fungal consortia, similar to bacterial consortia, can also enhance the effectiveness of pest control strategies by combining different fungal species with complementary modes of action.

2.3 Viruses and their application in biocontrol

Viruses, particularly entomopathogenic viruses, are emerging as potent biocontrol agents against tea pests. In China, over 80 species of viruses have been identified as natural enemies of tea pests, and several viral insecticides have been commercialized for large-scale use (Ye et al., 2014). These viruses specifically target pest species, reducing their populations without affecting non-target organisms. The application of viral biocontrol agents is part of integrated pest management (IPM) programs, which aim to minimize chemical pesticide use and its associated environmental impacts (Rahman et al., 2018). The specificity and effectiveness of viral biocontrol agents make them a valuable tool in sustainable tea pest management. In summary, the integration of bacteria, fungi, and viruses as biocontrol agents offers a multifaceted approach to managing tea pests. Each group of microbes brings unique advantages, and their combined use can lead to more robust and sustainable pest control strategies.

3 Mechanisms of Action

3.1 Antibiosis and microbial antagonism

Antibiosis and microbial antagonism are critical mechanisms through which beneficial microbes exert control over tea pests. These mechanisms involve the production of antimicrobial compounds, enzymes, and secondary metabolites that inhibit the growth or activity of pathogens and pests. For instance, microbial consortia composed of beneficial bacteria and fungi have been shown to effectively control both root and foliar pathogens in tomato plants through direct microbial antagonism (Minchev et al., 2021). Similarly, *Actinobacteria*, a significant component of the rhizosphere microbiome, produce pest-antagonistic secondary metabolites and enzymes that contribute to pathogen suppression (Ebrahimi-Zarandi et al., 2022). The use of microbial bio-agents as elicitors in plant defense mechanisms also highlights the role of antibiosis, where microbes produce antimicrobial compounds that directly inhibit phytopathogens (Figure 1).

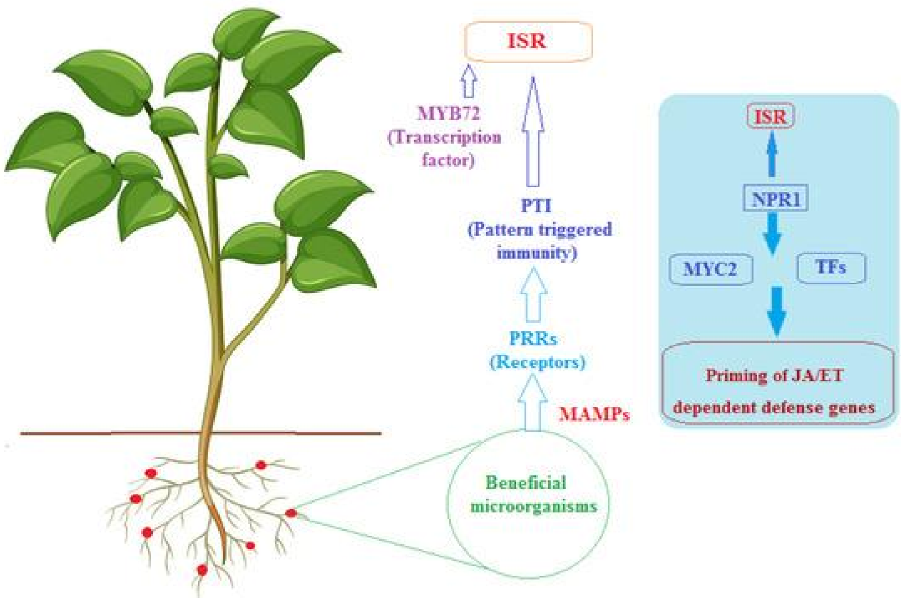

Figure 1 Induced systemic resistance (ISR) by beneficial microorganisms (Adopted from Ebrahimi-Zarandi et al., 2022)
Image caption: JA and ET are central regulators phytohormones of ISR, and transcription factors (e.g., MYC2) mediate the increased responsiveness of this pathway to stimulation, known as priming. Transcription factor MYB72, as a root-specific transcription factor and early signaling factor, functions as a node of convergence in ISR elicited by beneficial microbes. (ET, ethylene; JA, jasmonic acid; NPR1, NONEXPRESSOR OF PR GENES1; MAMPs, microbe-associated molecular patterns; PRRs, plant recognition receptors; PTI, PAMP-triggered immunity; TFs, transcription factors) (Adopted from Ebrahimi-Zarandi et al., 2022)

Ebrahimi-Zarandi et al. (2022) found that induced systemic resistance (ISR) is a crucial defense mechanism in plants activated by beneficial microorganisms in the rhizosphere. This process is regulated primarily by the phytohormones jasmonic acid (JA) and ethylene (ET), which enhance the plant's defensive capabilities. The root-specific transcription factor MYB72 plays a pivotal role in early ISR signaling, serving as a convergence point for signals from beneficial microbes. Additionally, ISR involves the pattern triggered immunity (PTI) pathway, which is mediated by plant recognition receptors (PRRs) detecting microbe-associated molecular patterns (MAMPs). Key transcription factors such as MYC2 further prime the plant's defense genes for enhanced responsiveness. This priming effect ensures that upon subsequent attacks, the plant's defense response is more robust and effective, contributing to an overall improved resilience against pathogens.

3.2 Induced systemic resistance in plants

Induced systemic resistance (ISR) is a plant defense mechanism activated by beneficial microbes, leading to enhanced resistance against a broad spectrum of pathogens and pests. ISR involves long-distance systemic signaling within the plant, often mediated by jasmonic acid (JA) and ethylene (ET) pathways, although salicylic acid (SA) can also play a role (Yu et al., 2022). Beneficial microbes trigger ISR, priming the plant's immune system for rapid and robust responses to pathogen invasions. This mechanism has been extensively studied in various crops, including tea, where microbial pesticides have been employed to counteract mite and insect pest damage. The activation of ISR by beneficial microbes not only enhances plant immunity but also contributes to sustainable pest management practices by reducing reliance on chemical pesticides (Zehra et al., 2021).

3.3 Direct parasitism and predation

Direct parasitism and predation by beneficial microbes are effective biological control strategies against tea pests. Entomopathogenic microorganisms (EM), such as fungi, nematodes, viruses, and bacteria, directly infect and kill insect pests, providing a natural and eco-friendly alternative to chemical pesticides (Deka et al., 2022). The efficiency of entomopathogenic microorganisms against various tea pests has been demonstrated, with microbial biopesticides showing promising effects in controlling pest populations (Deka and Babu, 2021). Additionally, the role of microorganisms in indirect pest biological control, such as enhancing plant defense responses and attracting natural enemies, further supports the use of direct parasitism and predation in integrated pest management (IPM) strategies. By harnessing these mechanisms of action, beneficial microbes offer a sustainable and effective approach to managing tea pests, reducing the environmental impact of chemical pesticides, and promoting agricultural sustainability.

4 Case Studies in Tea Plantations

4.1 Successful bacterial biocontrol in tea

Bacterial biocontrol agents have shown significant promise in managing tea pests and diseases. In North East India, the application of locally isolated bacteria such as *Azotobacter*, *Azospirillum*, *Bacillus*, and *Pseudomonas* has been integrated into disease management strategies. These bacteria, when used in combination with low doses of chemical fungicides and botanical extracts, have demonstrated a reduction in disease severity by up to 78.2% (Sarmah et al., 2020). Additionally, endophytic actinobacteria, particularly Streptomyces strains, have been identified for their plant growth-promoting and biocontrol traits. These strains not only enhance plant growth but also suppress major fungal pathogens (Figure 2), making them effective bioinoculants for sustainable tea cultivation (Hazarika et al., 2022).

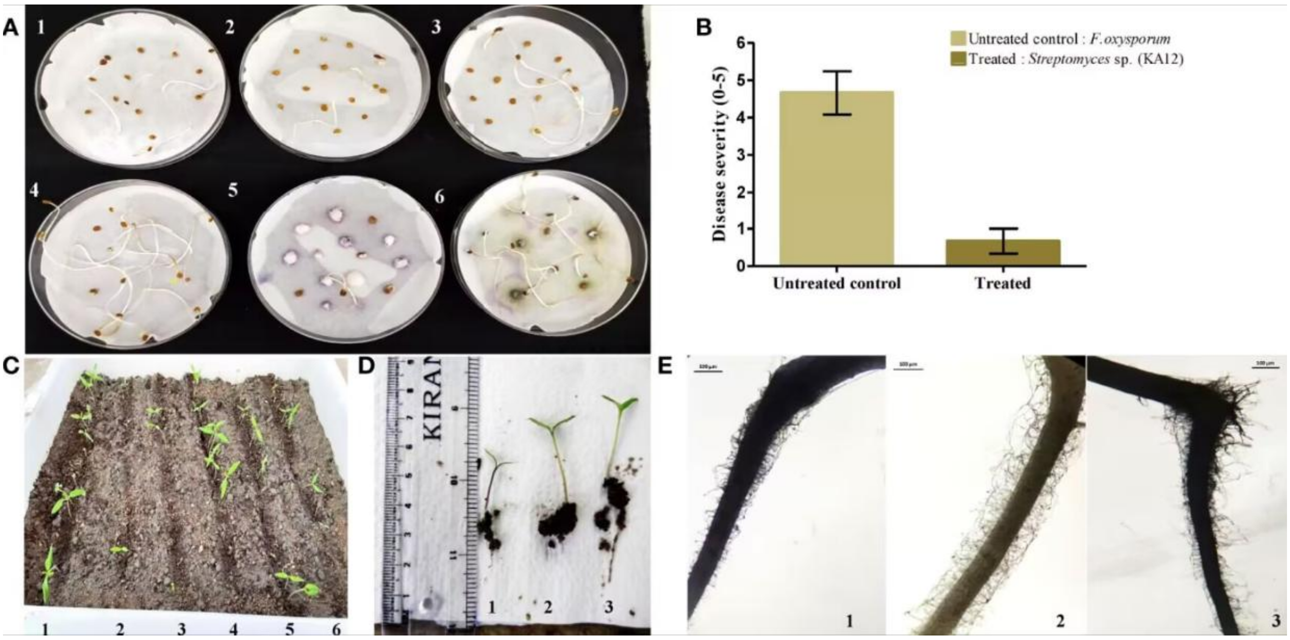

Figure 2 Evaluation of induced systemic resistance and seed germination (Adopted from Hazarika et al., 2022)

Image caption: (A) Seed germination plate assay (1,2,3) Control. Non-bacterized tomato seeds, (4) KA12 bacterized seeds, (5) *F. oxysporum* inoculated seeds, (6) KA12 bacterized seeds, and *F. oxysporum* inoculated (B) Degree of disease severity in control and inoculated seeds. (C) In-planta seed germination assay. (1) Bacterized tomato seeds, (2, 3, 5, 6) non-bacterized control seeds, (4) *F. oxysporum* inoculated seeds, (D) growth after 14 days of germination, (1) un-inoculated control, (2) KA12 and *F. oxysporum* inoculated, (3) KA12 inoculated. (E) Stereomicroscopic visualization of root hairs after 14 days of seed germination (1) Un-inoculated control (2) KA12 inoculated (3) Inoculated with KA12 and *F. oxysporum*. Scale 100 µm (Adopted from Hazarika et al., 2022)

Hazarika et al. (2022) found that the treatment of tomato seeds with *Streptomyces* sp. (KA12) significantly enhances seed germination and reduces disease severity caused by *Fusarium oxysporum*. The study demonstrated that bacterized seeds (treated with KA12) showed better germination rates compared to non-bacterized control seeds and those inoculated with *F. oxysporum*. In-planta assays confirmed these findings, with KA12-treated seeds exhibiting robust growth and reduced pathogen impact after 14 days. Stereomicroscopic analysis revealed that root hairs of KA12-inoculated seedlings were more developed compared to controls, indicating better root health and resilience. Overall, the application of beneficial microorganisms like *Streptomyces* sp. (KA12) can effectively induce systemic resistance in plants, enhancing growth and providing protection against pathogens.

4.2 Fungal applications in tea pest management

Fungal biocontrol agents have also been effectively utilized in tea plantations. *Trichoderma* species, known for their antagonistic properties against a wide range of plant pathogens, have been extensively studied and commercialized as biocontrol agents. These fungi contribute to the suppression of soil-borne diseases and enhance plant health through various mechanisms, including mycoparasitism and the production of antimicrobial compounds. In addition, the use of aerated vermicompost tea (ACT) combined with fungal biocontrol agents like *Clonostachys rosea* has shown promising results in suppressing pathogens such as *Fusarium* and *Rhizoctonia*, further supporting the potential of fungal applications in tea pest management (Wylie and Punja, 2020).

4.3 Viral biocontrol strategies in tea cultivation

Viral biocontrol strategies, though less commonly discussed, offer a unique approach to managing tea pests. Mycoviruses, which infect and confer hypovirulence to plant pathogenic fungi, have been explored as a means to control fungal diseases in various crops. The exploitation of mycoviruses in tea cultivation could potentially reduce the virulence of fungal pathogens, thereby minimizing the impact of diseases on tea plants (Sarrocco, 2023). This approach aligns with the broader goal of developing sustainable and environmentally friendly pest management strategies in tea plantations. By integrating bacterial, fungal, and viral biocontrol agents, tea plantations can achieve a more holistic and sustainable approach to pest management, reducing reliance on chemical pesticides and promoting overall plant health.

5 Integration with Other Pest Management Strategies

5.1 Combining biocontrol with chemical methods

The integration of biological control agents (BCAs) with chemical methods can enhance the effectiveness of pest management strategies while reducing the negative impacts of chemical pesticides. For instance, the use of microbial biocides in combination with low doses of new fungicide molecules has shown promising results in managing tea diseases. This approach not only reduces the chemical load but also promotes sustainable tea cultivation by maintaining soil fertility and supporting native microbial populations (Sarmah et al., 2020). Additionally, combining BCAs with chemical treatments can improve the reliability and efficacy of pest control, as demonstrated in postharvest disease management where BCAs were used alongside nutrient additives and physical treatments to achieve results comparable to synthetic pesticides.

5.2 Integration with cultural and mechanical controls

Cultural and mechanical controls, such as crop rotation, sanitation, and physical barriers, can be effectively integrated with biological control strategies to manage tea pests. The use of microbial consortia, which includes beneficial bacteria and fungi, can enhance plant defense mechanisms and improve the overall health of the tea plants. This approach has been shown to control a wide range of plant diseases and pests, thereby reducing the reliance on chemical pesticides (Minchev et al., 2021) (Figure 3). Furthermore, the application of BCAs at specific growth stages, such as flowering, can induce a "path dependency" that enhances the plant's natural defense mechanisms and improves the establishment of beneficial microbes (Sare et al., 2021).

Minchev et al. (2021) found that microbial inoculation significantly impacts the survival of tomato seedlings in soil infected with the pathogen *Fusarium oxysporum*. Treatments with beneficial microbes, especially the consortia SynCom1A and SynCom2A, demonstrated high seedling survival rates, comparable to the non-diseased control. Individual microbial strains such as *Bacillus amyloliquefaciens* and *Pseudomonas chlororaphis* also improved survival but to a lesser extent. The treatment with *Trichoderma harzianum*, particularly strain 22, was notably effective in enhancing seedling survival. These findings suggest that utilizing specific microbial consortia or strains can mitigate the adverse effects of soil-borne pathogens and promote plant health. This approach offers a promising strategy for sustainable agriculture by leveraging beneficial microorganisms to enhance crop resilience against diseases.

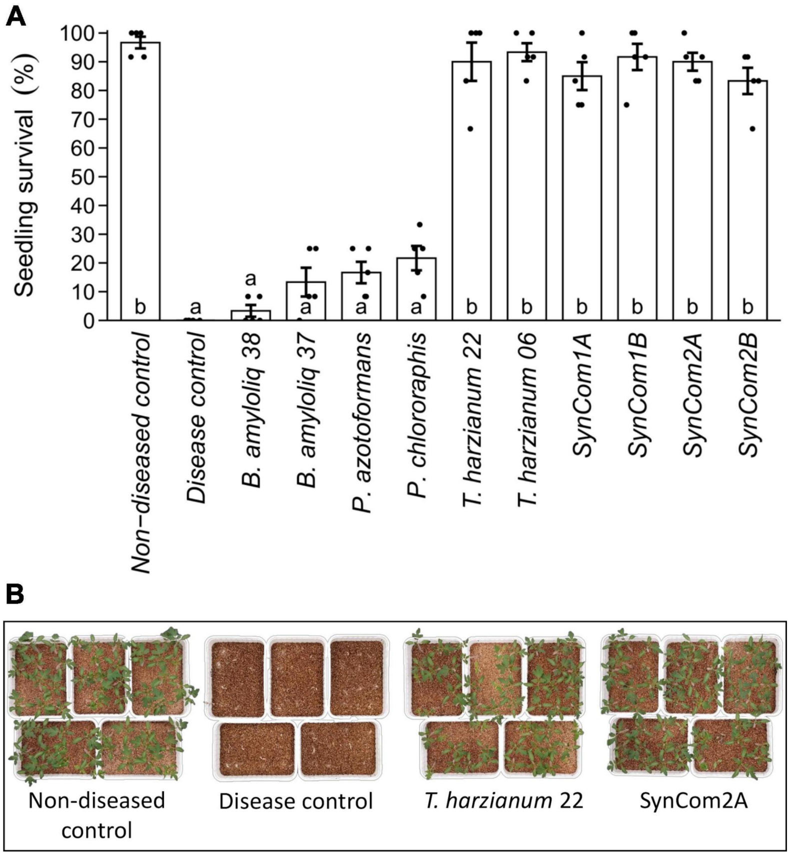

Figure 3 Effect of microbial inoculation on disease caused by the soil-borne pathogen *Fusarium oxysporum* (Adopted from Minchev et al., 2021)

Image caption: (A) Survival of tomato plants after 15 days of growth in *F. oxysporum*-infected soil. Seeds were either water-inoculated ("disease control") or inoculated with the individual or consortia treatments. A "non-diseased control" was also included, where water-inoculated seeds were sown in soil without *F. oxysporum*. Single strains were inoculated at 1×10^7 cfu/plant and the consortia were inoculated at the same concentration for each microorganism (SynCom1A, SynCom2A) or at 1×10^7 cfu/plant total microbial concentration (SynCom1B, SynCom2B). Bars represent predicted mean ± SE of the probability of seedling survival based on a generalized linear model with binomial distribution and logit link function. Black dots represent raw data points. Treatments not sharing a letter in common are significantly different based on the Tukey honestly significant difference (HSD) test ($p < 0.05$, n = 5). (B) Survival of plant seedlings in *F. oxysporum*-infected soil. Pictures illustrate plant survival in non-diseased and disease control, *Trichoderma harzianum*, and SynCom2A treatments (Adapted from Minchev et al., 2021)

5.3 Synergy with genetic and breeding approaches

The synergy between biological control strategies and genetic or breeding approaches can lead to the development of more resilient tea plants. By understanding the genetic basis of beneficial plant-microbe interactions, researchers can breed "microbe-optimized crops" that are better suited to support and benefit from microbial biocontrol agents (Rahman et al., 2018). This approach not only enhances the plant's natural defense mechanisms but also increases the efficacy and reliability of biocontrol strategies. Additionally, the use of entomopathogenic microorganisms has shown promising results in controlling tea pests, suggesting that integrating these microbes with genetically improved tea varieties could further enhance pest management outcomes (Deka and Babu, 2021).

6 Environmental and Economic Impacts

6.1 Environmental benefits of microbial biocontrol

Microbial biocontrol strategies offer significant environmental benefits compared to traditional chemical pesticides. The use of entomopathogenic microorganisms (EM) such as fungi, nematodes, viruses, and bacteria has been shown to effectively manage tea pests while minimizing environmental contamination and pesticide residues (Sare et al., 2021). These microbial agents are eco-friendly alternatives that help maintain soil fertility and biodiversity, crucial for sustainable tea cultivation. Additionally, microbial biocontrol agents can be integrated into existing pest management systems, reducing the reliance on synthetic chemicals and promoting a healthier ecosystem (Rahman et al., 2018).

6.2 Cost-effectiveness of biological control strategies

Biological control strategies using microbial agents are not only environmentally beneficial but also cost-effective. The application of microbial consortia, which includes carefully selected and compatible beneficial microorganisms, has demonstrated extended functionality and effectiveness in controlling a wide range of plant diseases, thereby reducing the need for multiple chemical treatments. This approach can lead to significant cost savings for tea growers by decreasing the expenditure on chemical pesticides and mitigating the economic losses associated with pest resistance and crop damage (Deka et al., 2022). Furthermore, the development and commercialization of microbial biopesticides have shown promising results in field trials, indicating their potential for widespread adoption in the tea industry (Sarmah et al., 2020).

6.3 Long-term sustainability and market impact

The long-term sustainability of microbial biocontrol strategies is evident in their ability to provide consistent pest management while preserving the ecological balance of tea plantations. The use of microbial biocides has been shown to reduce disease severity significantly, promoting sustainable tea cultivation practices. Moreover, ecological pest management (EPM) approaches, which incorporate microbial biocontrol agents, have been associated with improved tea biomass, quality, and economic returns. These sustainable practices not only enhance the resilience of tea production systems but also contribute to the overall marketability of tea by ensuring lower pesticide residues and higher quality products (Idris et al., 2020). The positive environmental and economic impacts of microbial biocontrol strategies underscore their potential to transform tea pest management and support the long-term viability of the tea industry.

7 Challenges and Limitations

7.1 Challenges in microbial biocontrol application

The application of microbial biocontrol agents in tea plantations faces several challenges. One significant issue is the inconsistency in the effectiveness of biocontrol agents under field conditions. While laboratory results are often promising, translating these findings to the field can be problematic due to environmental variability and the complex interactions within the ecosystem (Rahman et al., 2018). Additionally, the formulation and delivery methods of microbial consortia need to be optimized to ensure the survival and efficacy of the microbes in diverse environmental conditions (Minchev et al., 2021). Another challenge is the potential for non-target effects, where beneficial microbes might inadvertently affect non-target organisms, including beneficial insects or native microbial communities.

7.2 Limitations in current research and practices

Current research on microbial biocontrol is still in its nascent stages, with many studies focusing on a limited number of microbial strains and their interactions with specific pests or pathogens. This narrow focus can limit the generalizability of findings and the development of broad-spectrum biocontrol agents (Qadri et al., 2020). Moreover, there is a lack of comprehensive understanding of the complex interactions between microbial biocontrol agents, plants, and pests, which hinders the development of more effective and reliable biocontrol strategies. The scalability of laboratory findings to field applications remains a significant hurdle, as does the need for more extensive field trials to validate the efficacy and safety of these biocontrol agents.

7.3 Regulatory and public acceptance issues

Regulatory frameworks for the approval and use of microbial biocontrol agents are often stringent and can vary significantly between regions, posing a barrier to the widespread adoption of these technologies. The process of gaining regulatory approval can be time-consuming and costly, which may deter investment and innovation in this field. Additionally, public acceptance of microbial biocontrol agents can be a challenge, as there may be concerns about the safety and environmental impact of introducing new microorganisms into agricultural ecosystems.

Educating the public and stakeholders about the benefits and safety of microbial biocontrol is crucial for gaining broader acceptance and support for these sustainable agricultural practices (Minchev et al., 2021).

8 Future Research Directions

8.1 Emerging trends in microbial biocontrol research

Recent advancements in microbial biocontrol research have highlighted the potential of microbial consortia over single-strain applications. Studies have shown that microbial consortia, composed of carefully selected and compatible beneficial microorganisms, can effectively control a wider range of plant diseases through diverse mechanisms and application methods (Minchev et al., 2021). This trend is gaining traction as it offers a more versatile and reliable approach to biological control. Additionally, the concept of "plant-optimized microbiomes" and "microbe-optimized crops" is emerging, where microbiome engineering and breeding strategies are employed to enhance plant-microbe interactions for better pest and disease management (Rahman et al., 2018).

8.2 Technological advancements and innovations

Technological advancements are playing a crucial role in the development of microbial biocontrol strategies. Innovations in microbiome manipulation, such as the use of microbial biocides and the integration of organic amendments with beneficial microbes, are providing new avenues for sustainable pest management. The development of microbial-based tools for insect pest management, including the discovery of novel biopesticides and the improvement of mass-reared insects' performance for autocidal programs, is also noteworthy (Qadri et al., 2020). These technological innovations are paving the way for more effective and environmentally friendly pest control solutions.

8.3 Integration of microbial biocontrol with advanced agricultural practices

The integration of microbial biocontrol with advanced agricultural practices, such as Integrated Pest Management (IPM) and organic farming, is essential for achieving sustainable agriculture. IPM strategies that incorporate microbial biocontrol agents can reduce the reliance on chemical pesticides and enhance plant defense mechanisms against pests (Francis et al., 2020). Furthermore, the use of aerated vermicompost tea combined with microbial biological control agents has shown promise in suppressing plant pathogens in organic greenhouse vegetable production. This integration not only improves disease suppression but also promotes soil health and crop productivity. In conclusion, future research should focus on optimizing microbial consortia, leveraging technological advancements, and integrating microbial biocontrol with advanced agricultural practices to harness the full potential of beneficial microbes in pest management. By doing so, we can develop more sustainable and effective strategies for controlling tea pests and enhancing crop productivity.

9 Concluding Remarks

The utilization of beneficial microbes for biological control in tea cultivation has shown promising results in managing pests and diseases while promoting sustainable agricultural practices. Research has demonstrated that microbial biocontrol agents, including bacteria, fungi, and viruses, can effectively control a variety of tea pests such as mites, leafhoppers, and pathogens. These microbes not only reduce pest populations but also enhance plant growth and resilience by modulating plant defense mechanisms and altering root exudates to recruit beneficial rhizosphere microbiomes. The application of microbial consortia has been particularly effective, offering extended functionality and stability in controlling multiple pathogens. Moreover, the integration of microbial biocontrol agents into Integrated Pest Management (IPM) strategies has been shown to reduce reliance on chemical pesticides, thereby minimizing environmental contamination and pesticide residues in tea products.

Future research should focus on the following areas to enhance the efficacy and adoption of microbial biocontrol strategies in tea cultivation: Microbial Consortia Optimization: Further studies are needed to optimize the composition and application methods of microbial consortia to ensure consistent and reliable pest control across different environmental conditions. Mechanistic Understanding: Investigate the underlying mechanisms by which beneficial microbes enhance plant defense and growth, including the role of root exudates and plant-microbe interactions. Field Trials and Scalability: Conduct extensive field trials to validate laboratory findings and develop scalable application technologies that can be easily adopted by tea growers. Regulatory and Safety Assessments: Ensure that microbial biocontrol agents are safe for non-target organisms and comply with regulatory standards. This includes conducting comprehensive safety assessments and obtaining necessary approvals for commercial use. Farmer Education and Training: Implement educational programs to train tea farmers on the benefits and application techniques of microbial biocontrol agents, promoting wider adoption and integration into existing IPM practices.

Beneficial microbes hold significant potential in transforming tea cultivation into a more sustainable and environmentally friendly practice. By reducing the dependency on chemical pesticides, microbial biocontrol agents not only mitigate the adverse effects of synthetic chemicals on the environment and human health but also contribute to the long-term health and productivity of tea plantations. The successful integration of these biological control strategies into IPM frameworks can lead to more resilient tea ecosystems, improved crop yields, and higher quality tea products. As research continues to advance, the role of beneficial microbes in sustainable tea cultivation is expected to expand, offering new opportunities for innovation and growth in the tea industry.

Acknowledgments

The HortHerb Publisher appreciate the feedback from two anonymous peer reviewers on the manuscript of this study, whose careful evaluation and constructive suggestions have contributed to the improvement of the manuscript.

Funding

This work was supported by the National Natural Science Foundation of China (No. 32160077), the Guizhou Academy of Agricultural Sciences Talent Special Project [grant number (2022-02 and 2023-02)].

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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