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Role and Application Strategies of Biocontrol Bacteria in Sustainable Agricultural Development

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Abstract

In the contemporary context of global agriculture, confronted with numerous challenges including ecological degradation, chemical pesticide misuse and food safety concerns, biocontrol bacteria are garnering increased attention as a green and sustainable approach to disease prevention and control. This paper systematically explores the mechanisms by which biocontrol bacteria promote healthy crop growth, inhibit pathogenic microorganisms, improve soil ecosystems and reduce chemical inputs, from the perspective of sustainable agricultural development. The paper synthesises current research and industrial development at home and abroad, highlighting the application of biocontrol bacteria, including Bacillus spp., Pseudomonas spp. and Streptomyces spp., in disease control of rice, wheat, tomato and other crops. The paper demonstrates the potential of biocontrol bacteria in driving the green transformation of agriculture. A thorough analysis was conducted on the key issues, including the unstable field application effect, the weak adaptability of strains, the outdated formulation process, and the inadequate market and policy support. Based on these findings, targeted application strategies were proposed from the dimensions of strain selection and breeding, formulation optimization, technology integration, and policy guidance. Finally, the trend of the deep integration of biocontrol bacteria with the frontiers of histotechnology, smart agriculture, and agricultural carbon neutrality is anticipated. The paper's objective is twofold: firstly, to provide a theoretical foundation and technical reference framework for in-depth research and practical application of biocontrol bacteria in the sustainable development of agriculture; and secondly, to offer a comprehensive review of the current state of research and practical application of biocontrol bacteria in the sustainable development of agriculture.

Keywords

biological control; sustainable agricultural development; plant disease control; microbial agents;

I. Introduction

1.1 Background of the Study

Agriculture, as a fundamental industry for human survival and social development, has been facing significant ecological and environmental challenges in recent years. The rapid growth of the global population has led to a significant increase in demand for food, resulting in a substantial reliance on chemical pesticides and fertilisers to achieve high and stable yields in

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agricultural production. However, the utilisation of conventional chemical control methodologies, though efficacious in the short term, has given rise to a plethora of environmental and ecological concerns, including, but not limited to, soil contamination, eutrophication of water bodies, a precipitous decline in biodiversity, and the emergence of pest resistance, which have had a deleterious effect on the health and sustainable development of agroecosystems [1, 2].

Consequently, the necessity for a resolution to the aforementioned environmental issues has given rise to the notion of sustainable agriculture. The Food and Agriculture Organization of the United Nations (FAO) has proposed a sustainable agricultural development model that aims to achieve harmonious unity of economic, ecological and social benefits. The overarching objective of sustainable agriculture is to ensure long-term food security while minimising environmental degradation and maintaining ecosystem stability and diversity [3].

Consequently, the development of effective eco-friendly crop protection strategies that can gradually replace or reduce the reliance on chemical pesticides is an inevitable trend and a significant research direction in achieving sustainable agricultural development.

1.2 Concepts and research status of biocontrol bacteria

Among the many paths for sustainable agricultural development, biological control technology has received widespread attention for its environmentally friendly, efficient and low-cost characteristics. In this context, microbial biocontrol methods, predominantly those derived from bacteria, have emerged as a primary focus of research. Biocontrol bacteria have been shown to inhibit or control plant pathogenic microorganisms, protect plants from disease infection, and promote plant growth through mechanisms such as competition, parasitism, antagonism, or induction of plant disease resistance [4].

Notable biocontrol bacteria include Bacillus spp., Pseudomonas fluorescens (Pseudomonas spp.) and Streptomyces spp.Recent years have seen a proliferation of research findings on biocontrol bacteria, with a substantial number of experiments and field applications demonstrating their clear advantages and potential in the suppression of plant diseases, the reduction of pesticide residues, the enhancement of soil microbiology and the promotion of plant growth [5,6]. However, the practical application of bioprophylactic bacteria is also faced with numerous challenges, including low stability, poor environmental adaptability, technical limitations in large-scale production, and low acceptance by farmers, which limits its widespread promotion in agricultural production [7].

Consequently, there is a necessity for in-depth study of the role of antibacterial in the sustainable development of agriculture mechanism, optimisation of the application strategy, and overcoming of the technical bottlenecks, in order to establish these as important research directions in the field of agricultural science at present.

II. Important role of biocontrol bacteria in sustainable agricultural development

As people's understanding of sustainable development in agriculture deepens, an increasing number of studies are demonstrating the significant role of biocontrol bacteria in promoting eco-friendly agriculture. These bacteria have been shown to improve crop yield and quality, as well as guaranteeing food safety. The following aspects primarily demonstrate these functions:

2.1 Positive effects of biocontrol bacteria on agro-ecosystems

The extensive utilisation of chemical pesticides in agricultural production has engendered profound ecological and environmental concerns, encompassing soil and water contamination,

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substantial biodiversity decline, and augmented resistance of pathogenic bacteria [1]. In comparison with conventional chemical control methodologies, biocontrol bacteria, as an environmentally friendly disease control instrument, offer the following ecological benefits:

Firstly, biocontrol bacteria are environmentally safe and eco-friendly. These bacteria originate from natural ecosystems and possess inherent ecological safety, and are generally harmless to non-target organisms such as pollinators, birds and soil animals, with low ecological risks [8]. For instance, the use of Bacillus subtilis (Bacillus subtilis) does not result in substantial ecological impacts and is naturally degradable in soil and water bodies [9].

Secondly, the employment of biocontrol bacteria can assist in the reduction of chemical pesticides, thereby minimising the risk of pesticide residues. Research has demonstrated that the employment of biocontrol bacteria can effectively substitute for certain chemical pesticides, thereby significantly reducing the chemical pollution load on the environment during agricultural production and promoting the stability and balance of agroecosystems [10].

Furthermore, the application of biocontrol bacteria has been demonstrated to enhance the soil microbiological environment and promote soil health. It is widely acknowledged that soil health is a significant indicator of sustainable agricultural development. The activities of biocontrol bacteria in the soil have been shown to increase the diversity of beneficial microbial communities and to inhibit the overpopulation of pathogenic microorganisms. This, in turn, maintains the stability of the soil ecosystem and enhances soil resilience [11]. For instance, it has been demonstrated that the colonisation of soil by Bacillus and Pseudomonas fluorescens can lead to a substantial augmentation in the diversity of soil microbial communities, thereby promoting soil nutrient cycling and, consequently, enhancing crop yield and quality [12].

2.2 Role of biocontrol bacteria in improving crop yield and quality

The application of biocontrol bacteria has been demonstrated to enhance crop yield and quality through a number of direct and indirect mechanisms. These mechanisms of action include, but are not limited to, a plant growth-promoting role (PGPR role) and effective disease control.

A significant proportion of biocontrol bacteria also possess a plant growth-promoting function and are designated as plant growth-promoting rhizobacteria (PGPR). These bacteria promote plant growth through mechanisms such as nitrogen fixation, phosphorus solubilisation, and production of phytohormones (e.g., IAA, gibberellin), thereby improving crop yield and quality [13]. For instance, Pseudomonas fluorescens strains have been observed to enhance root growth and yield in grain crops such as wheat and maize [14].

Conversely, the effective prevention and control of diseases by biocontrol bacteria also indirectly improves crop yield and quality. By impeding the propagation and infestation of noxious bacteria and reducing the incidence of diseases, crops can flourish, thereby ensuring higher yields and enhancing product quality [15]. For instance, several strains of the genus Bacillus have been shown to exert a substantial control over economically significant crop diseases, including tomato green blight, cucumber blight, and rice blight, thereby leading to a notable enhancement in crop yields and market value [16].

2.3 Role of Biocontrol Bacteria in Safeguarding Agricultural Economic Efficiency and Food Safety

The popularisation and application of biocontrol bacteria has also demonstrated significant advantages in terms of safeguarding agricultural economic benefits and ensuring food safety. The capacity of biocontrol bacteria to curtail the utilisation of chemical pesticides has been

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demonstrated to engender a substantial diminution in pesticide residues in agricultural products. This, in turn, has been shown to enhance food safety, to ensure compliance with increasingly rigorous market standards, and to augment the competitiveness and market value of agricultural products [17].

Furthermore, biocontrol bacterial formulations are typically derived from natural strains, are relatively inexpensive to produce, and have a long-term effect on the soil environment, thereby reducing agricultural production costs, increasing the economic returns of farmers, and promoting the stable development of the agricultural economy [18]. For instance, the promotion of biocontrol bacterial agents in certain developing countries has been shown to have a significant impact on farmers' income, thereby promoting the virtuous cycle of the agricultural economy [19].

III. Current status and successful cases of the application of biocontrol bacteria in agriculture

As the global population demands greater environmental protection and food safety, the utilisation of biocontrol bacteria in agricultural practices has increased significantly. These bacteria are notable for their ecological safety and their capacity to effectively prevent and control diseases. Presently, various types of biocontrol bacteria are undergoing industrialisation, exhibiting substantial efficacy in disease management across numerous crop species, thereby significantly contributing to the sustainable advancement of agriculture.

3.1 Main applications and mechanisms of action of different types of biocontrol bacteria

At present, the biocontrol bacteria most frequently employed are principally concentrated within three predominant genera: namely, Bacillus spp., Pseudomonas spp. and Streptomyces spp. The efficacious management of diseases is accomplished by these bacteria through a range of biocontrol mechanisms.

(1) Bacillus genus (Bacillus spp.)

Bacillus spp. has an extremely wide range of applications due to its characteristics of spore formation and environmental adaptability. Its biological defence mechanism mainly includes:

Secretion of antibiotics: for example, Bacillus subtilis (Bacillus subtilis) can synthesise a variety of antibiotics such as Bacilysin and Iturin, which effectively inhibit the growth of plant pathogens [20].

Inducing plant systemic resistance (ISR): e.g. Bacillus amyloliquefaciens (Bacillus amyloliquefaciens) induces systemic resistance in plants and improves their disease resistance [21].

Competition for ecological niches: rapid occupation of plant inter-root ecological niches prevents colonisation by pathogenic bacteria.

(2) Pseudomonas spp.

Pseudomonas fluorescens and other species are widely used for their broad-spectrum antagonistic properties. The main mechanisms include:

Production of iron carriers: capture iron by secreting iron carriers (Siderophore), resulting in the inability of pathogenic bacteria to grow normally due to iron deficiency [22].

Production of broad-spectrum antimicrobial substances: such as Pyrrolnitrin , which directly kills pathogenic bacteria [23].

Induces a defence response in plants: enhances the plant's own defence system [24].

(3) Streptomyces spp.

Streptomyces spp are important soil actinomycetes with a broad spectrum of bacterial inhibition and the main mechanisms are:

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Secretion of a variety of antibiotics: e.g., Streptomyces griseoviridis can produce a variety of secondary metabolites, which effectively inhibit the growth of pathogenic bacteria [25].

Secretion of chitinase and glucanase: degrades pathogenic fungal cell walls [19].

Stimulates plant growth-promoting effects: produces growth hormone-like hormones and mineral solubility to promote plant growth [14].

3.2 Successful cases of biocontrol bacteria in disease control of different crops

(1) The management of rice diseases

Rice blight has been a significant disease that has restricted rice production. Research has demonstrated that the application of a fungicide derived from Bacillus subtilis can substantially mitigate the occurrence of rice blight and enhance rice yield. For instance, Jamali et al. (2020) reported that the application of Bacillus subtilis fungicide prevented rice blight by more than 70%, thereby significantly enhancing the quality and yield of rice [26].

(2) Wheat disease control cases

Wheat blast disease is a serious threat to wheat yield and food safety. Research on the use of Pseudomonas fluorescens to control wheat blast has made positive progress. For example, Wang et al. (2021) found that the use of Pseudomonas fluorescens to treat wheat seeds can effectively inhibit the infestation of Rhizoctonia solani, with a field preventive effect of 60-80%, and reduce the contamination of erythromycotoxins and significantly improve the quality of wheat [27]. In addition to this, lv et al. (2024) found that the efficacy of Bacillus beleriensis in the control of a new type of wheat leaf blight was 95.4%, which significantly reduced the impact of this disease on wheat [39].

3.3 Current status of research and development and industrial application of biocontrol bacterial agents

Recent years have seen significant advancements in the field of industrial biocontrol, with bacterial agents playing a pivotal role. Europe and the United States have achieved large-scale industrial production of biocontrol agents based on Bacillus spp. and Pseudomonas spp. For example, Bacillus spp. preparations under the trade name of 'Serenade' have been widely used around the world, successfully preventing and controlling a variety of diseases and obtaining the widespread acceptance of farmers [28].

Concurrently, China has also progressively established an industrial infrastructure and attained noteworthy outcomes in the realm of marketing. Notable examples include the Bacillus formulations developed by Ningbo Green Garden Biotechnology Company, which have been extensively utilised in the control of diseases affecting cucumber and tomato crops, yielding substantial economic and ecological benefits.

Despite the emergence of industrial applications for biocontrol agents, challenges persist, including product instability and inadequate market acceptance. It is imperative to augment scientific research endeavours, optimise formulation and processes, and foster the healthy and expeditious development of the biocontrol fungicide industry through policy guidance and farmer education.

IV. Challenges and problems in the application of biocontrol bacteria

Although biocontrol bacteria have shown remarkable results in agricultural disease control and play an important role in promoting sustainable agricultural development, they still face many challenges in their practical application. These problems mainly include unstable field application, limited environmental adaptability of biocontrol strains, immature

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commercialisation technology system, and insufficient policy and market support. The systematic analysis of these problems and the discussion of their causes will help to promote the wider and more effective implementation of biocontrol technology in practice.

4.1 Instability in the Effects of Field Application

The antagonistic effects of biocontrol bacteria are typically observed to be effective under laboratory or greenhouse conditions. However, their control effects frequently prove to be unstable in field environments, primarily due to the following factors:(1) Interference from environmental conditions. The field environment is complex and variable, including temperature, humidity, soil pH, precipitation, light and so on, which may affect the survival and activity of biocontrol bacteria. For instance, elevated temperatures may impede the metabolic activity of certain biocontrol bacteria, while excessively moist or arid soil conditions may curtail their capacity for colonisation [22].

Secondly, the physiological status of the host plant must be considered. The root exudates of plants have been demonstrated to influence the structure of inter-root microbial communities [29]. In instances where the host plant is experiencing stress, its inter-root environment may become disadvantageous for the growth and functional expression of biocontrol bacteria.

(3) Interaction with indigenous microorganisms. Field soils contain diverse and intricate microbial communities, and biocontrol bacteria must compete with them for ecological niches and nutrient resources. Consequently, achieving effective colonisation or maintaining dominant populations can be challenging [30].

The combination of these factors leads to obvious differences in the application of the same biocontrol strain in different regions or crops, which is a major obstacle to the promotion of its application.

4.2 The limited adaptability and stability of biocontrol strains

At present, the biocontrol bacteria most frequently used are wild-type strains that have been selected in nature. These strains have the following problems:

(1) Poor genetic stability. Some strains are prone to gene loss or mutation in successive generations or field use, resulting in reduced functional expression. For instance, some Bacillus subtilis strains have lost their capacity to produce antibiotics under elevated temperatures, thereby compromising the efficacy of biocontrol [31].

(2) High specificity and poor generalisability. It has been demonstrated that certain biocontrol strains demonstrate efficacy exclusively in the context of specific pathogens or specific crops, thereby impeding their application across diverse crops and disease systems [32].

Thirdly, there is a weak capacity for colonisation. It is difficult for biocontrol bacteria to form stable communities in the inter-root or foliar surface of crops, and their physiological activities are subject to environmental fluctuations, thus affecting the holding period [33].

Consequently, enhancing the broad-spectrum, stability and ecological adaptability of bacterial strains is a pivotal direction for the selection and engineering improvement of biocontrol strains in the future.

4.3 Immature Biocontrol Preparation Development and Process Technology

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The process of developing biocontrol agents, from the initial screening of strains to their commercialisation, is a complex one. However, there are still evident shortcomings in relation to the following aspects:

(1) The use of a single dosage form. The majority of biocontrol fungicides are currently in simple formulations such as wet powder and wettable powder, which are difficult to meet the diversified field application needs. In contrast, foreign countries have a wider range of products on the market, including liquid suspensions, slow-release capsules, granules and other high stability products [8].

Secondly, the carrier material is not optimal. Commonly used carriers such as talcum powder and sodium humate are susceptible to moisture absorption or inactivation under conditions of high humidity or temperature, thereby compromising the vitality of the bacteria [34].

Thirdly, there is the issue of the short shelf life of preparations. The absence of systematic protection technology (e.g. freeze-drying, microcapsule embedding) has a significant impact on the shelf life of most biocontrol bacterial agents, which are difficult to circulate.

Furthermore, the technical requirements for application vary according to formulation, whether by spraying, drip irrigation, seed mixing, etc., necessitating higher concentrations of live bacteria and more favourable environmental conditions, which in turn affects their universality and operability across different crops and cultivation modes.

4.4 Insufficient policy guidance and market acceptance

Despite the significant ecological benefits of biocontrol bacterial products, their market share in the agricultural sector remains comparatively low in relation to that of chemical pesticides. The primary reasons for this include:

(1) Delayed regulatory and certification mechanisms. Some countries lack clear standards and green channels for microbial pesticide registration and management, and the long product registration period and high cost constrain the development of the industry [35].

Secondly, there is insufficient knowledge of these products among farmers. A substantial proportion of farmers have limited understanding of biopesticides, are concerned about their inconsistent effectiveness or unwieldy operation, and often persist in utilising fast-acting chemicals [36].

(3) The absence of a price advantage is also a salient issue. At present, the price of some high-activity and high-purity biopesticides is still higher than that of ordinary chemical pesticides, and the economic drive is insufficient.

It is therefore recommended that the government introduce incentive policies, such as green subsidies, special promotion funds, and the establishment of a sound industry standard system, in order to guarantee the large-scale application of biocontrol bacteria.

V. Strategies and prospects for the application of biocontrol bacteria for sustainable agricultural development

As the importance of biocontrol bacteria in the sustainable development of agriculture is increasingly recognised, the question of how to scientifically and systematically promote its wide application in production practice has become a key proposition for the development of current agricultural technology. In this chapter, we will discuss the optimisation strategies for practical application, countermeasures at the levels of technology research and development, industrial promotion and policy system, and the future direction of research and development.

5.1 Screening and Function Enhancement Strategies of Highly Efficient Biocontrol Strains

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The application of biocontrol bacteria is contingent upon the possession of advantageous strains that are highly active, broad-spectrum and adaptable. The following aspects are currently the focus of screening and improvement strategies for strains:(1) Establishment of multi-dimensional screening system: a multi-indicator comprehensive evaluation system should be constructed from the dimensions of ecological niche specificity, antiretroviral resistance, colonisation ability, bacterial inhibition spectrum and bioprophilic potential to conduct high-throughput screening of natural strain resources in ecosystems, such as soil and inter-root of plants.

(2) Introduction of genetic engineering and synthetic biology tools: through CRISPR-Cas9, genome rearrangement, anabolic pathway construction and other means, we can accurately enhance the antagonistic substance synthesis ability, adversity adaptability and biofilm formation ability of biocontrol strains.

(3) Construction of SynCom: Research has demonstrated that there is metabolic complementation and ecological niche synergy among different strains, and the use of multibacterial compounding or artificial microbial communities (Synthetic microbial communities) can enhance the stability and broad-spectrum of the biocontrol system [37].

5.2 Optimisation of formulation technologies and construction of application systems

The successful application of biocontrol bacteria is contingent on the development of effective formulations and the establishment of appropriate application systems. Optimisation strategies encompass the following:

(1) Diversified formulation development: on the basis of traditional wet powder, promote a variety of dosage forms, such as liquid fermentation concentrates, granules, and microencapsulated embedding agents, in order to adapt to different crops, application modes and environmental conditions. For instance, microcapsule technology can protect the bacterium from ultraviolet rays and high temperatures, whilst simultaneously improving the holding period in the field.

Secondly, standardisation of application technology systems is imperative. This involves establishing application parameter standards for different crops, diseases and environmental conditions, including application time, application site (foliar, inter-root, seed), frequency of use, etc., to ensure stable and reproducible effects.

(3) Combined application strategy: the synergistic application of biocontrol bacteria in conjunction with organic fertilisers, biochar, humic acid, antioxidant-inducing agents and other agricultural inputs, with the objective of exerting synergistic composite effects such as anti-disease, bioprophylaxis and water retention.

5.3 Extension models for integrating biocontrol bacteria with the green transformation of agriculture

As a pivotal instrument in the realm of green prevention and control, the incorporation of biocontrol bacteria into the national agricultural green development strategy system is imperative to foster its institutionalisation, scale-up, and routine implementation. The establishment of a collaborative mechanism between research institutions, enterprises, and farmers is paramount. The integration of bacterial strain development, formulation production and technical services should be strengthened through enhanced technical cooperation between research institutions and enterprises. Concurrently, farmers' cooperatives and the

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agricultural extension system should be utilised to enhance farmers' acceptance of the technology and ensure optimal application rates.

(2) The promotion of the construction of regional green prevention and control demonstration zones is also recommended: with major grain and vegetable production areas as the core, the establishment of regional demonstration bases for green prevention and control of pests and diseases is advised, with the integration of biocontrol bacteria with other green technologies, and the promotion of the demonstration-driven effect.

(3) The establishment of product quality traceability and certification systems: the development of green certification, geographical indication agricultural products and other systems, the incorporation of biocontrol bacteria into standard specifications, and the enhancement of the market premium capacity of green agricultural products.

5.4 Prospective trends in research and development

In the future, research and application of biocontrol bacteria will be subject to the following trends:

Precision prevention and control driven by the microbiome: based on macro-genome, transcriptome and metabolome analyses, interactions between biocontrol bacteria and pathogens, plants and the environment will be accurately analysed, and research and development of biocontrol bacteria with customized targets will be promoted.

Integration with digital agriculture: The integration of remote sensing monitoring, sensors, intelligent spraying equipment and other agricultural Internet of Things (IoT) technologies will facilitate the precise and targeted application of biocontrol fungi, thereby enhancing the utilisation of resources and response speed.

Participation in the construction of farmland carbon sinks and climate resilience: The incorporation of biocidal bacteria has been demonstrated to promote plant growth and improve soil structure. It is hypothesised that this will be incorporated into the research system of agricultural carbon emission reduction and stress management, and to enhance the climate resilience of the agricultural system.

VI. Conclusion

In the context of global agriculture facing multiple pressures, including climate change, ecological degradation and food safety, the exploration of low environmental load, efficient and sustainable disease prevention and control strategies has become an inevitable choice for the development of agricultural science and technology [38]. As a form of environmentally sustainable control resource, biocontrol bacteria (biocontrol bacteria) have become a significant technical support force for the sustainable development of agriculture due to their ecological friendliness, diverse antagonistic mechanisms, and strong sustainability.

This paper aims to provide a comprehensive overview of the mechanisms of biocontrol bacteria, their current applications, notable success cases, the practical challenges they face, and their future development prospects. Research has demonstrated that biocontrol bacteria can effectively inhibit plant pathogens through various mechanisms (e.g., producing antibiotics, competing for ecological niches, and inducing plant systemic resistance), while also promoting plant growth, improving soil health, and reducing the use of chemical pesticides. This is of great significance for enhancing the stability of agroecosystems and the green transformation of crop production systems.

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However, in the actual promotion process, the application of biocontrol bacteria still faces problems such as poor field adaptability, insufficient formulation stability, and low market recognition. To address these challenges, it is imperative to promote technological optimisation, strain engineering, reconstruction of application modes, policy guidance, and other levels. In the future, research and practice should be strengthened in the following aspects:

The following objectives are to be pursued:

1) To deepen the understanding of the interaction mechanism between biocontrol bacteria and plant-pathogen-environment by means of histology and systems biology;

2) To promote the research and development of artificial flora and multifunctional compound preparations to enhance broad-spectrum and resistance;

3) To establish standardised application specifications and industrial technology systems to achieve high-quality and sustainable products in practice;

4) To leverage digital agriculture and green certification systems to create a new green prevention and control model integrating 'biocontrol + ecology + industry'.

The advancement of biocontrol bacterial technology is poised to play a pivotal role in catalysing the green transformation of conventional agriculture. Beyond this, it is anticipated that this technology will assume an increasingly significant function in the realm of global agro-ecological restoration, efficient resource utilisation, and agro-climatic resilience. In the future, agricultural development should prioritise not only the maximisation of yield, but also transition towards a multi-win pattern of harmonious coexistence between human and nature. In this new paradigm, biocontrol bacteria will undoubtedly play a pivotal role.

Reference

[1] Carvalho, F. P. (2017). Pesticides, environment, and food safety. Food and Energy Security, 6(2), 48-60. https://doi.org/10.1002/fes3.108

[2] Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. Interdisciplinary toxicology, 2(1), 1–12. https://doi.org/10.2478/v10102-009-0001-7

[3] FAO (2018). Transforming food and agriculture to achieve the SDGs. Food and Agriculture Organization of the United Nations, Rome, Italy.

[4] Compant, S., Duffy, B., Nowak, J., Clément, C., & Barka, E. A. (2005). Use of plant growth-promoting bacteria for biocontrol of plant diseases: principles, mechanisms of action, and future prospects. Applied and environmental microbiology, 71(9), 4951–4959. https://doi.org/10.1128/AEM.71.9.4951-4959.2005

[5] Kumar, A., Singh, V. K., Tripathi, V., Singh, P. P., & Singh, A. K. (2018). Plant Growth-Promoting Rhizobacteria (PGPR): Perspective in Agriculture Under Biotic and Abiotic Stress. In R. Prasad, S. S. Gill, & N. Tuteja (Eds.), *Crop Improvement Through Microbial Biotechnology* (pp. 333-342). Elsevier. https://doi.org/10.1016/B978-0-444-63987-5.00016-5

[6] Keswani, C., Singh, H. B., García-Estrada, C., Caradus, J., He, Y. W., Mezaache-Aichour, S., Glare, T. R., Borriss, R., & Sansinenea, E. (2020). Antimicrobial secondary metabolites from agriculturally important bacteria as next-generation pesticides. Applied microbiology and biotechnology, 104(3), 1013–1034. https://doi.org/10.1007/s00253-019-10300-8

[7] O'Brien, P.A. Biological control of plant diseases. Australasian Plant Pathol. 46, 293–304 (2017). https://doi.org/10.1007/s13313-017-0481-4

ISSN: 3079-6679

[8] Montesinos E. (2003). Development, registration and commercialization of microbial pesticides for plant protection. International microbiology : the official journal of the Spanish Society for Microbiology, 6(4), 245–252. https://doi.org/10.1007/s10123-003-0144-x

[9] Shafi, J., Tian, H., & Ji, M. (2017). Bacillus species as versatile weapons for plant pathogens: a review. Biotechnology & Biotechnological Equipment, 31(3), 446–459. https://doi.org/10.1080/13102818.2017.1286950

[10] Harman G. E. (2000). Myths and Dogmas of Biocontrol Changes in Perceptions Derived from Research on Trichoderma harzinum T-22. Plant disease, 84(4), 377–393. https://doi.org/10.1094/PDIS.2000.84.4.377

[11] Bender, S. F., Wagg, C., & van der Heijden, M. G. A. (2016). An Underground Revolution: Biodiversity and Soil Ecological Engineering for Agricultural Sustainability. Trends in ecology & evolution, 31(6), 440–452. https://doi.org/10.1016/j.tree.2016.02.016

[12] Mendes, R., Garbeva, P., & Raaijmakers, J. M. (2013). The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS microbiology reviews, 37(5), 634–663. https://doi.org/10.1111/1574-6976.12028

[13] Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. Annual review of microbiology, 63, 541–556. https://doi.org/10.1146/annurev.micro.62.081307.162918

[14] Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World journal of microbiology & biotechnology, 28(4), 1327–1350. https://doi.org/10.1007/s11274-011-0979-9

[15] Raaijmakers, J. M., Vlami, M., & de Souza, J. T. (2002). Antibiotic production by bacterial biocontrol agents. Antonie van Leeuwenhoek, 81(1-4), 537–547. https://doi.org/10.1023/a:1020501420831

[16] Chowdhury, S. P., Hartmann, A., Gao, X., & Borriss, R. (2015). Biocontrol mechanism by root-associated Bacillus amyloliquefaciens FZB42 - a review. Frontiers in microbiology, 6, 780. https://doi.org/10.3389/fmicb.2015.00780

[17] Aktar, M. W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: their benefits and hazards. Interdisciplinary toxicology, 2(1), 1–12. https://doi.org/10.2478/v10102-009-0001-7

[18] Alabouvette, C., Olivain, C. & Steinberg, C. Biological Control of Plant Diseases: The European Situation. Eur J Plant Pathol 114, 329–341 (2006). https://doi.org/10.1007/s10658-005-0233-0

[19] Pal, K.K. and Gardener, B.M. (2006) Biological Control of Plant Pathogens. The Plant Health Instructor, 2, 1117-1142.

https://doi.org/10.1094/PHI-A-2006-1117-02

[20] Fira, D., Dimkić, I., Berić, T., Lozo, J., & Stanković, S. (2018). Biological control of plant pathogens by Bacillus species. Journal of biotechnology, 285, 44–55. https://doi.org/10.1016/j.jbiotec.2018.07.044

[21] Chowdhury, S. P., Hartmann, A., Gao, X., & Borriss, R. (2015). Biocontrol mechanism by root-associated Bacillus amyloliquefaciens FZB42 - a review. Frontiers in microbiology, 6, 780. https://doi.org/10.3389/fmicb.2015.00780

[22] Haas, D., & Défago, G. (2005). Biological control of soil-borne pathogens by fluorescent pseudomonads. Nature reviews. Microbiology, 3(4), 307–319. https://doi.org/10.1038/nrmicro1129

[23] Raaijmakers, J. M., De Bruijn, I., Nybroe, O., & Ongena, M. (2010). Natural functions of lipopeptides from Bacillus and Pseudomonas: more than surfactants and antibiotics. FEMS microbiology reviews, 34(6), 1037–1062. https://doi.org/10.1111/j.1574-6976.2010.00221.x

[24] Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., & Bakker, P. A. (2014). Induced systemic resistance by beneficial microbes. Annual review of phytopathology, 52, 347–375. https://doi.org/10.1146/annurev-phyto-082712-102340

[25] Law, J. W., Ser, H. L., Khan, T. M., Chuah, L. H., Pusparajah, P., Chan, K. G., Goh, B. H., & Lee, L. H. (2017). The Potential of Streptomyces as Biocontrol Agents against the Rice Blast Fungus, Magnaporthe oryzae (Pyricularia oryzae). Frontiers in microbiology, 8, 3. https://doi.org/10.3389/fmicb.2017.00003

[26] Jamali, H., Sharma, A., Roohi, & Srivastava, A. K. (2020). Biocontrol potential of Bacillus subtilis RH5 against sheath blight of rice caused by Rhizoctonia solani. Journal of basic microbiology, 60(3), 268–280. https://doi.org/10.1002/jobm.201900347

[27] Wang, L. Y., Xie, Y. S., Cui, Y. Y., Xu, J., He, W., Chen, H. G., & Guo, J. H. (2015). Conjunctively screening of biocontrol agents (BCAs) against fusarium root rot and fusarium head blight caused by Fusarium graminearum. Microbiological Research, 177, 34-42. https://doi.org/10.1016/j.micres.2015.05.005

[28] Rajamani, M., Negi, A. (2021). Biopesticides for Pest Management. In: Venkatramanan, V., Shah, S., Prasad, R. (eds) Sustainable Bioeconomy . Springer, Singapore. https://doi.org/10.1007/978-981-15-7321-7_11

[29] Berendsen, R. L., Pieterse, C. M., & Bakker, P. A. (2012). The rhizosphere microbiome and plant health. Trends in plant science, 17(8), 478–486. https://doi.org/10.1016/j.tplants.2012.04.001

[30] Compant, S., Samad, A., Faist, H., & Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. Journal of advanced research, 19, 29–37. https://doi.org/10.1016/j.jare.2019.03.004

[31] Romero, D., de Vicente, A., Rakotoaly, R. H., Dufour, S. E., Veening, J. W., Arrebola, E., Cazorla, F. M., Kuipers, O. P., Paquot, M., & Pérez-García, A. (2007). The iturin and fengycin families of lipopeptides are key factors in antagonism of Bacillus subtilis toward Podosphaera fusca. Molecular plant-microbe interactions : MPMI, 20(4), 430–440. https://doi.org/10.1094/MPMI-20-4-0430

[32] Mercado-Blanco, J., & Bakker, P. A. (2007). Interactions between plants and beneficial Pseudomonas spp.: exploiting bacterial traits for crop protection. Antonie van Leeuwenhoek, 92(4), 367–389. https://doi.org/10.1007/s10482-007-9167-1

[33] Bashan, Y. and Bashan, L.E. (2010) How the Plant Growth-Promoting Bacterium Azospirillum Promotes Plant Growth—A Critical Assessment. Advances in Agronomy, 108, 77-136.
https://www.researchgate.net/publication/251449020

[34] Glare, T., Caradus, J., Gelernter, W., Jackson, T., Keyhani, N., Köhl, J., Marrone, P., Morin, L., & Stewart, A. (2012). Have biopesticides come of age?. Trends in biotechnology, 30(5), 250–258. https://doi.org/10.1016/j.tibtech.2012.01.003

[35] Bailey, K. L., Boyetchko, S. M., & Längle, T. (2010). Social and economic drivers shaping the future of biological control: A Canadian perspective on the factors affecting the development and use of microbial biopesticides. Biological Control, 52(3), 221-229. https://doi.org/10.1016/j.biocontrol.2009.05.003

[36] Choudhary, D. K., & Johri, B. N. (2009). Interactions of Bacillus spp. and plants--with special reference to induced systemic resistance (ISR). Microbiological research, 164(5), 493–513. https://doi.org/10.1016/j.micres.2008.08.007

[37] Vorholt, J. A., Vogel, C., Carlström, C. I., & Müller, D. B. (2017). Establishing Causality: Opportunities of Synthetic Communities for Plant Microbiome Research. Cell host & microbe, 22(2), 142–155. https://doi.org/10.1016/j.chom.2017.07.004

ISSN: 3079-6679

[38] Yi Hu, & Ye Chen. (2025). Genetic Modification Technology and Food Security: Opportunities, Challenges and Response Strategies. Global Academic Frontiers, 3(1), 11-27. https://doi.org/10.5281/zenodo.15074505

[39] Huanggang Normal University. (2024). A strain of Paenibacillus barensis B2 and its application in the control of wheat leaf blight: 202410195641.0 [P]. June 7, 2024.