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PROSPECTS FOR THE USE OF MICROORGANISMS WITH ANTAGONISTIC PROPERTIES AGAINST PHYTOPATHOGENIC FUNGI IN GREENHOUSE AGROECOSYSTEMS

Kuldosheva Malokhat Abdumalik Kizi
Master's Student, Group MBIO-S-251U
Samarkand Branch of Kimyo International
University in Tashkent, Samarkand, Uzbekistan
Mamadoliev Ikrom Ilkhomidinovich
Associate Professor, Head of the Department of Fundamental Medical Sciences
Samarkand Branch of Kimyo International
University in Tashkent, Samarkand, Uzbekistan
E-mail: boburmed6886@gmail.com
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Abstract: This article examines the prospects for the biological protection of plants against phytopathogenic fungi in greenhouse agroecosystems. Elevated temperatures and relative humidity, restricted air circulation, excessive moisture in growing substrates and soil, and high planting density create favorable conditions for the development and spread of phytopathogenic microorganisms. The prolonged and repeated application of chemical fungicides may contribute to the development of resistance in pathogen populations, the accumulation of pesticide residues in agricultural products, and disturbances in the microbial balance of agroecosystems. Consequently, the application of microorganisms possessing antagonistic properties represents a promising approach to environmentally sustainable and integrated plant protection.

The analysis indicates that microorganisms belonging to the genera Trichoderma, Bacillus, Pseudomonas, and certain species of Streptomyces possess multiple biological mechanisms for suppressing phytopathogenic fungi. The principal mechanisms include mycoparasitism, competition for nutrients and ecological niches, the production of antimicrobial metabolites and hydrolytic enzymes, siderophore synthesis, and the induction of systemic resistance in plants. Under greenhouse conditions, the effectiveness of antagonistic microorganisms depends on microclimatic parameters, strain-specific characteristics, application methods, formulation stability, and the developmental stage of the target pathogen.

The article discusses approaches to selecting effective antagonistic microorganisms, evaluating their performance under laboratory and greenhouse conditions, adjusting application rates according to monitoring data, and integrating biological agents into comprehensive plant protection systems. The application of antagonistic microorganisms as components of an integrated biological control strategy, rather than as isolated biological products, is considered a promising approach to sustainable greenhouse crop production.

Keywords: greenhouse agroecosystem, phytopathogenic fungi, biological control, antagonistic microorganisms, Trichoderma, Bacillus, Pseudomonas, mycoparasitism, antimicrobial metabolites, integrated plant protection.

Introduction

Greenhouse cultivation represents an intensive agricultural production system in which environmental parameters, including temperature, humidity, light, mineral nutrition, and irrigation regimes, can be regulated. However, the controlled environmental conditions that promote plant

growth may also create favorable ecological conditions for various phytopathogenic microorganisms, including fungi and fungus-like organisms. High relative humidity, condensation on leaf surfaces, excessive substrate moisture, insufficient air circulation, and high planting density increase the risk of disease development and transmission.

In greenhouse agroecosystems, phytopathogens such as Fusarium, Botrytis, Rhizoctonia, Pythium, Sclerotinia, Alternaria, and other pathogenic organisms can cause root rot, stem and leaf infections, fruit decay, and wilting syndromes in various crops. These diseases negatively affect plant growth and development, reduce crop productivity, and deteriorate the quality of agricultural products.

Chemical fungicides have traditionally been among the principal methods used to control phytopathogenic organisms. Nevertheless, repeated fungicide applications have raised concerns regarding the development of resistance in pathogen populations, pesticide residues in agricultural products, and adverse effects on beneficial microorganisms. Therefore, integrating biological control agents into comprehensive plant protection systems has considerable scientific and practical significance.

The greenhouse biological control protocol provided for this study also emphasizes the importance of linking biological agent applications with monitoring procedures, microclimatic parameters, and adaptive management strategies. In particular, the effectiveness of biological control is influenced by temperature, relative humidity, the viability of biological agents, and their application methods.

An important advantage of antagonistic microorganisms is their ability to suppress phytopathogens through several biological mechanisms. For example, Trichoderma species may inhibit phytopathogenic fungi through mycoparasitism, competition for nutrients and space, and the production of hydrolytic enzymes and secondary metabolites. Similarly, Bacillus species are characterized by their ability to produce lipopeptides, siderophores, and lytic enzymes, as well as stimulate plant defense responses.

The objective of this study is to analyze the scientific foundations, mechanisms of action, factors influencing effectiveness, and prospects for integrating microorganisms with antagonistic properties into biological protection systems against phytopathogenic fungi in greenhouse agroecosystems.

Literature Review

The concept of using antagonistic microorganisms for the biological control of phytopathogens is based on the regulation of plant–microorganism interactions. Among the most extensively investigated biological control agents are microorganisms belonging to the genera Trichoderma, Bacillus, Pseudomonas, and Streptomyces, along with other beneficial microorganisms.

Antagonistic Properties of Trichoderma Species

Trichoderma species are among the most extensively studied microorganisms used in the biological control of phytopathogenic fungi. Their principal advantage is associated with their ability to exhibit several mechanisms of antagonistic activity simultaneously.

The first mechanism is mycoparasitism. During this process, Trichoderma hyphae establish direct contact with the hyphae of pathogenic fungi, coil around them, and degrade their cell walls through the activity of enzymes such as chitinases, β-1,3-glucanases, and proteases.

The second mechanism involves competition for nutrients and ecological space. Owing to their rapid growth and ability to colonize the rhizosphere, Trichoderma species reduce the availability of ecological niches and nutritional resources required by phytopathogenic microorganisms.

The third mechanism is antibiosis. Certain Trichoderma strains produce secondary metabolites and volatile organic compounds capable of inhibiting the growth of phytopathogenic fungi. Scientific

literature emphasizes that these mechanisms provide a basis for using Trichoderma as a broad-spectrum biological control agent.

The fourth important mechanism is the activation of plant defense systems. Certain Trichoderma strains can enhance induced systemic resistance in plants. Consequently, protective responses may also be strengthened in plant tissues that have not been in direct contact with the pathogen.

Biological Control Potential of Bacillus Species

Bacteria belonging to the genus Bacillus are also considered promising biological control agents against phytopathogenic fungi. One of their important characteristics is their ability to form endospores, which may provide practical advantages during the formulation and storage of biological preparations.

Lipopeptides such as surfactin, iturin, and fengycin, synthesized by Bacillus subtilis and related species, may affect the growth and development of various phytopathogenic fungi. Furthermore, the production of siderophores and hydrolytic enzymes enhances competition for nutrients and contributes to pathogen suppression.

Pseudomonas and Other Rhizosphere Microorganisms

Pseudomonas species are distinguished by their ability to actively colonize the rhizosphere, produce siderophores and antimicrobial compounds, and promote plant growth. Consequently, their potential application in integrated biological control programs targeting rhizosphere-associated pathogens is being investigated.

Streptomyces species and other beneficial microorganisms are also regarded as potential biological control agents because of their capacity to synthesize antibiotic compounds, enzymes, and siderophores that may inhibit phytopathogenic microorganisms.

Overall, contemporary research indicates that the biological activity of microbial control agents is not restricted to a single mechanism. Competition, antibiosis, mycoparasitism, enzymatic degradation, and the induction of plant immunity may function as complementary mechanisms.

Research Methodology

This article is based on an analytical and theoretical research approach involving the systematization of scientific literature concerning the application of antagonistic microorganisms against phytopathogenic fungi and practical materials related to greenhouse biological control protocols.

The research methodology included the following stages.

Systematic analysis of scientific literature. The biological characteristics of Trichoderma, Bacillus, Pseudomonas, and other microorganisms involved in the suppression of phytopathogenic organisms were analyzed.

Classification of antagonistic mechanisms. The principal mechanisms, including mycoparasitism, competition, antibiosis, enzymatic activity, siderophore synthesis, and the induction of systemic plant resistance, were examined as distinct categories.

Analysis of greenhouse microclimatic factors. Temperature, relative humidity, substrate moisture, leaf wetness, air circulation, and planting density were considered the principal environmental factors influencing the effectiveness of biological control agents.

Monitoring-based approach. Biological control in greenhouse environments should be based on monitoring results. The protocol considered in this study identifies visual inspection, sample collection, and systematic recording of microclimatic parameters as essential components of biological control management.

Adaptive management principles. The application rate and treatment interval of biological agents were considered adjustable parameters rather than components of a permanently fixed

application schedule. These parameters should be reassessed according to pathogen pressure, microclimatic conditions, and the observed effectiveness of biological preparations.

Integrated plant protection principles. The proposed approach involves combining biological agents with preventive agricultural practices, sanitation measures, microclimate management, and, where necessary, selective chemical control methods.

Results and Analysis

Principal Mechanisms of Action of Antagonistic Microorganisms

The analysis indicates that antagonistic microorganisms may suppress phytopathogenic fungi through several principal biological mechanisms.

Mechanism	Principal microorganisms	Characteristics of action
Mycoparasitism	Trichoderma	Direct parasitism and degradation of pathogenic fungal hyphae
Nutrient competition	Trichoderma, Bacillus, Pseudomonas	Competition for nutrients and ecological niches
Antibiosis	Trichoderma, Bacillus, Pseudomonas, Streptomyces	Suppression of pathogens through antimicrobial metabolites
Enzymatic activity	Trichoderma, Bacillus	Production of chitinases, glucanases, proteases, and other enzymes
Siderophore production	Bacillus, Pseudomonas	Restriction of pathogen growth through iron sequestration
Induced systemic resistance	Trichoderma, Bacillus, Pseudomonas	Activation of internal plant defense mechanisms

The combined action of these mechanisms constitutes an important characteristic of antagonistic microorganisms. Unlike biological control approaches based on a single mechanism, multifactorial antagonistic activity enables more comprehensive management of interactions among pathogens, plants, and beneficial microorganisms.

Importance of Greenhouse Microclimatic Conditions

High antagonistic activity demonstrated by a microorganism under laboratory conditions does not necessarily guarantee equivalent effectiveness under greenhouse conditions. One of the principal reasons is the variability of microclimatic parameters.

Elevated humidity may favor the colonization and development of certain microbial biological control agents. However, excessive moisture may simultaneously promote the spread of phytopathogenic organisms. Therefore, biological control should not be limited to the application of microbial preparations but should be implemented in combination with appropriate microclimate management.

The greenhouse biological control protocol considered in this study also recommends monitoring temperature, relative humidity, substrate moisture, and leaf wetness.

Algorithm for Selecting Biological Control Agents

The following sequence is considered appropriate when selecting microorganisms for controlling specific phytopathogens:

Pathogen identification → Assessment of environmental conditions favoring pathogen development → Selection of an antagonistic strain → Laboratory evaluation of antagonistic activity → Greenhouse trials → Determination of application rates and treatment intervals → Monitoring → Adjustment based on observed results.

This process should consider the pathogen species, source of infection, stage of disease development, and phenological condition of the host plant.

Monitoring and Adaptive Application

The effectiveness of biological control under greenhouse conditions is closely associated with continuous monitoring.

The following parameters may be recorded during the monitoring process:

- Proportion of infected plants;
- Disease incidence and distribution;
- Intensity of disease development;
- Emergence of new infection sites;
- Air temperature;
- Relative humidity;
- Substrate moisture;
- Leaf surface wetness.

The existing protocol proposes integrating visual observations, sample collection, and digital technologies into the monitoring process. The application of Internet of Things (IoT) sensors and digital monitoring systems enables real-time observation of microclimatic conditions and supports data-driven decision-making.

A Prospective Model for Applying Antagonistic Microorganisms

A future biological protection system for greenhouse agroecosystems may be organized according to the following sequence:

Phytosanitary monitoring → Early pathogen detection → Selection of antagonistic microorganisms → Preventive or early therapeutic application → Microclimate adjustment → Reassessment after 7–10 days → Adjustment of application rates and intervals according to effectiveness.

The fundamental principle of this approach is not to maximize the quantity of biological agents applied, but rather to maintain an optimal biological application level corresponding to pathogen pressure.

The protocol proposes a model linking biological agent dosage to pest population density, economic injury thresholds, and agent effectiveness. For phytopathogenic fungi, this approach may be adapted using indicators of disease incidence and infection pressure.

Limitations of Biological Preparations

Despite their potential advantages, the application of antagonistic microorganisms is associated with several challenges.

The most important limitations include:

- Strain-specific effectiveness;
- Sensitivity to greenhouse microclimatic conditions;
- Storage stability of biological preparations;
- Changes in viable microorganism concentrations over time;
- Dependence of effectiveness on the developmental stage of the pathogen;
- Compatibility with other biological agents and fungicides;
- Differences between laboratory results and actual greenhouse performance.

Contemporary scientific literature also indicates that the effectiveness of biological agents based on Trichoderma and Bacillus is significantly influenced by strain characteristics, formulation, application technology, and environmental conditions.

Therefore, rather than considering a particular microorganism a universally effective biological control agent, it is scientifically more appropriate to evaluate its performance within the pathogen–plant–antagonist–microclimate system.

Conclusion

The application of antagonistic microorganisms for controlling phytopathogenic fungi in greenhouse agroecosystems represents a promising approach from both environmental and agrotechnological perspectives. Microorganisms belonging to the genera Trichoderma, Bacillus, Pseudomonas, and Streptomyces may suppress phytopathogenic organisms through multiple biological mechanisms.

The analysis indicates that mycoparasitism, competition for nutrients and ecological space, antibiosis, and the induction of plant defense responses are particularly important mechanisms associated with Trichoderma species. The ability of Bacillus and Pseudomonas species to produce antimicrobial metabolites, siderophores, and enzymes makes them promising biological agents for controlling rhizosphere-associated phytopathogens.

At the same time, evaluating the effectiveness of biological preparations solely on the basis of their antagonistic properties is insufficient. Greenhouse temperature, relative humidity, substrate moisture, planting density, pathogen developmental stage, and formulation characteristics must also be considered.

Practical Recommendations

Early detection of phytopathogenic organisms and regular phytosanitary monitoring should be established as essential components of biological protection programs in greenhouse agroecosystems.

The selection of Trichoderma, Bacillus, and Pseudomonas strains should be based on the identified pathogen and the cultivated crop species. Their antagonistic activity should initially be evaluated under laboratory conditions, followed by trials in controlled greenhouse environments.

Application rates and treatment intervals for biological preparations should not be determined exclusively according to fixed schedules. Instead, they should be adjusted through an adaptive management system based on disease incidence, disease development intensity, and monitoring results.

Furthermore, greenhouse humidity, air circulation, and condensation formation should be carefully regulated. When biological preparations are used in combination with fungicides, their biological compatibility should be assessed beforehand.

Future research directions include investigating microbial consortia composed of microorganisms with complementary mechanisms of action, isolating and standardizing highly active strains adapted to local crops and phytopathogens, and integrating IoT sensors and digital monitoring systems into biological protection algorithms.

The effectiveness of biological protection should be evaluated using comprehensive indicators, including disease incidence, disease severity indices, crop yield, and product quality.

Overall, the application of antagonistic microorganisms should be developed as a unified system based on the following principles:

Early diagnosis + Phytosanitary monitoring + Microclimate management + Adaptive biological control + Integrated plant protection.

Such an integrated approach may contribute to improving the sustainability, ecological safety, and effectiveness of greenhouse agricultural production.

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