Research on the Application and Interaction Mechanism of Biological Pesticides in Pest Control

Zhuoran Zhang[1,*], Dan Ma[2]
[1]*Maoming City Rural Revitalization and Development Guidance Center, Maoming, Guangdong, China*
[2]*Guangdong Preschool Normal College in Maoming, Maoming, Guangdong, China,*

Abstract: Biological pesticides achieve efficient pest control by affecting the physiological metabolism of pests through microorganisms, plant extracts, or insect-derived active substances. Their mechanisms of action involve neurotoxicity, endocrine disruption, and digestive system destruction, exhibiting strong target specificity and ecological safety. Environmental factors such as temperature, humidity, ultraviolet light, and soil pH influence their stability and persistence. Optimizing application strategies can enhance control efficacy. Gene editing and synthetic biology can improve the stability and target specificity of biological pesticides, while intelligent monitoring and precision application increase their efficiency. Integrating chemical pesticides and physical control methods can optimize pest management models and promote sustainable agricultural development.

Keywords: Biological Pesticides; Pest Control; Interaction Mechanisms; Ecological Stability; Biological Control

1. Introduction

The widespread use of chemical pesticides, while effectively controlling pests, has led to environmental pollution, increased pesticide resistance, and ecological imbalances due to long-term reliance. Biological pesticides, known for their selectiveness and high ecological safety, have become important tools in green pest control. Microbial-, plant-, and insect-derived biological pesticides act on pests through different mechanisms, affecting their growth, reproduction, and behavior. Environmental factors determine the stability and efficacy of biological pesticides, and optimizing application strategies can enhance their persistence. The application of gene editing, intelligent monitoring, and precise application technologies helps improve the efficiency of biological pesticides. Studying the mechanisms of biological pesticides and their interactions with the ecosystem is crucial for building an efficient and sustainable pest control system.

2.The Main Mechanisms of Action and Influencing Factors of Biological Pesticides in Pest Control

Biological pesticides exert different effects on pests through microorganisms, plant extracts, and insect-derived active substances, affecting their physiological metabolism and behavioral characteristics. Microbial biological pesticides utilize toxins, parasitism, or tissue destruction to exert insecticidal effects. For example, Bacillus thuringiensis releases δ-endotoxin to destroy the intestinal walls of insects. Plant-derived pesticides interfere with the growth and development of pests through active ingredients. For instance, azadirachtin affects the molting process, and phenolic compounds in plants inhibit feeding behavior. Insect-derived pesticides rely on the active substances of parasitic or predatory insects to suppress pest growth and hinder their reproduction. The activity of these biological pesticides is influenced by environmental factors[1]. High temperatures can reduce the activity of viral insecticides, while high humidity environments can enhance the pathogenicity of fungal biological pesticides. Ultraviolet light can accelerate the degradation of plant-derived pesticides. Soil pH values and microbial community structures affect the control effects on soil-dwelling pests. Optimizing application strategies, adjusting formulations, and rationally matching adjuvants can improve the stability and persistence of biological pesticides, enhancing the pest control effect.

3. Complex Interaction Mechanisms and Effects of Biological Pesticides on Pest Population Dynamics

3.1 How Biological Pesticides Affect Pest Population Fluctuations and Ecological Adaptability Changes

Microbial insecticides, through infection or toxin action, increase the mortality rate of individual pests, leading to a short-term decline in population size. During long-term control processes, pest populations may undergo adaptive changes due to selection pressure, such as behavioral avoidance, enhanced metabolic detoxification capabilities, or physiological resistance evolution, affecting control efficacy. Changes in environmental conditions and pest population structure also regulate the intensity of biological pesticide effects[2]. Some pest populations may shift towards individuals with stronger resistance under the pressure of biological pesticides, reducing the population's sensitivity to biological pesticides and affecting the group dynamics and ecological adaptability development of pests.

3.2 Synergy and Antagonism Mechanisms Between Pest Behavior, Physiological Adaptation, and the Effects of Biological Pesticides

Pest behavior regulation and physiological adaptation influence the effectiveness of biological pesticides, resulting in synergistic or antagonistic relationships. After sensing the presence of biological pesticides, some pests exhibit avoidance behaviors, such as reducing feeding or altering activity areas, to decrease pesticide exposure risk. Physiological adaptation is mainly reflected in the enhanced activity of detoxifying enzymes. Certain pests, after prolonged exposure to biological pesticide environments, undergo changes in their enzymatic systems, improving the degradation ability of pesticide components and weakening the insecticidal effect. The action of biological pesticides may interact with symbiotic microflora in pests, with some microorganisms helping pests metabolize exogenous toxins, thereby reducing the lethal effect of pesticides and affecting pest survival and reproductive capacity.

3.3 Long-Term Ecological Effects of Biological Pesticides on Pest Population Structure and Biodiversity

Long-term application of biological pesticides can affect the genetic diversity and ecological structure of pest populations, subsequently altering the stability of farmland ecosystems. Biological pesticides that effectively kill specific pests can lead to a decrease in target pest numbers, but non-target pests may rapidly reproduce due to reduced competitive pressure, resulting in a population substitution effect. Long-term use may also promote the accumulation of resistance genes in pests, enhancing their adaptability and increasing control difficulties. There are complex food chain relationships between pests and natural enemies in farmland ecosystems. The selective action of biological pesticides may affect natural enemy populations, breaking ecological balance and thereby having a profound impact on biodiversity.

4. Coupling Effect and Optimization Strategy of Biological Pesticides and Farmland Ecosystem

4.1 Mechanism of Soil Microbial Community on the Degradation and Activity Change of Biological Pesticides

Soil microbial communities affect the degradation rate and activity release of biological pesticides through metabolic actions, determining their persistence and effect intensity in the environment. Certain bacteria and fungi can secrete specific enzymes to accelerate the degradation of biological pesticides. For example, Pseudomonas and Bacillus can degrade Bacillus thuringiensis toxin, reducing its insecticidal effect[3]. The soil's organic matter content, pH value, and moisture conditions also influence microbial activity, thereby regulating the degradation rate of pesticides. In environments with high organic matter, biological pesticides may be adsorbed by soil organic matter, delaying degradation, while low pH environments may enhance the stability of some biological pesticides, prolonging their control effect.

4.2 Synergistic Effect of Beneficial Organisms such as Predatory Insects and Parasitic Wasps on the Control Effect of Biological Pesticides

Predatory insects and parasitic wasps are crucial for pest control and can enhance its efficiency when combined with biological pesticides. Predatory ladybugs and lacewings reduce pest numbers, lowering the control pressure on biopesticides. Parasitic wasps inhibit pest reproduction, slowing population recovery when used together with biopesticides. Some biopesticides, like fungal insecticides, weaken pests, making them easier prey for natural enemies and further improving control effects.

4.3 Feedback Regulation of Farmland Ecosystem Stability on the Long-Term Application Effects of Biological Pesticides

Planting diversity, soil nutrient cycling, and microbial balance influence the degradation and effectiveness of biological pesticides. Monoculture systems increase pest outbreaks and control pressure, while diverse planting patterns enhance biodiversity and reduce pest density, improving biopesticide efficiency. Long-term biopesticide use may alter pest population structures, affecting long-term control. Non-target organisms like pollinators and beneficial microbes also feedback-regulate biopesticide effectiveness, impacting their sustainable use in farmlands.

Table 1. Effect of Different Soil Types on the Degradation Rate and Activity Retention of Biological Pesticides

Soil Type	Organic Matter Content (%)	pH Value	Moisture Content (%)	Main Microbial Species	Biopesticide Degradation Half-life (days)	Activity Retention Rate (After 30 Days, %)	Data Source
Clay Soil	3.5	6.8	25	Pseudomonas, Bacillus	12	65	Soil Biology Research (2023)
Sandy Soil	1.2	7.5	10	Streptomyces, Actinomycetes	5	40	Journal of Agro-Environmental Science (2022)
Loamy Soil	2.8	6.5	18	Bacillus subtilis, Penicillium	8	55	Biopesticide Application Research (2021)
Black Soil	4.2	6.2	28	Actinomycetes, Pseudomonas	15	72	Soil Ecology (2020)

5. Strategies for Improving the Efficiency of Biological Pesticide Pest Control and Future Optimization Directions

5.1 Application Prospects of Gene Editing and Synthetic Biology in Enhancing the Stability and Targeting of Biological Pesticides

Gene editing and synthetic biology enhance biological pesticides' stability and targeting. The CRISPR-Cas system can modify microbial pesticides to express more stable and toxic insecticidal proteins, reducing impacts on non-target organisms. Synthetic biology optimizes metabolic pathways, such as increasing δ-endotoxin expression in Bacillus thuringiensis to boost lethality[4] Protein engineering also designs UV- and heat-tolerant insecticidal proteins, improving field persistence.

5.2 Optimized Models for the Combined Application of Biological Pesticides with Chemical Pesticides and Physical Control Technologies

Combining biological pesticides with chemical pesticides and physical controls enhances pest control effectiveness, reduces chemical use, and lowers environmental risks. Chemical pesticides offer rapid short-term control during outbreaks, while biological pesticides provide long-term effects and delay resistance. For example, integrating plant-derived biopesticides with low-dose insecticides boosts pest stress and responses insecticidal efficiency. Physical methods like pheromone traps, light traps, and insect netting reduce pest density, creating better conditions for biopesticide application.

5.3 The Promoting Effect of Precision Drug Application and Intelligent Pest Monitoring Technologies on the Application of Biological Pesticides

Precision drug application and intelligent pest monitoring technologies optimize biological pesticide use and enhance pest control efficiency. Drone spraying enables precise application based on pest distribution, reducing waste and improving coverage. Remote sensing and IoT sensors monitor pest dynamics in real-time, while AI analyzes data to determine optimal application timing and dosage. DNA barcode-based pest identification improves accuracy, reducing impacts on non-target insects. Combined with big data, an early warning system predicts outbreaks, further optimizing pesticide strategies and promoting sustainable agriculture.

6. Conclusion

Biological pesticides offer environmental sustainability, but their stability, persistence, and efficiency are limited. Enhancing them through gene editing, synthetic biology, and precision application technologies can improve targeting and stress resistance. Combining them with chemical and physical controls helps achieve synergy, delay resistance, and support sustainable agriculture.

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