Research Advances in the Control of Spider Mites Using Bioactive Substances of Biological Origin

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Abstract Spider mites are significant pests in agricultural production. The increasing resistance of spider mites, along with environmental pollution and ecological imbalance caused by their control, is primarily attributed to the long-term use of chemical acaricides in agriculture. In contrast, bioactive substances of biological origin offer advantages such as wide availability, environmental friendliness, and low tendency to induce resistance, making them a research hotspot for spider mite control. This review summarizes recent advances in the use of plant-derived active compounds (exemplified by extracts from Veratrum rhizomes), RNA interference (RNAi) technology, and microorganism-derived active substances for controlling spider mites. These bioactive agents exert acaricidal effects by disrupting the nervous system, interfering with metabolic processes, or silencing key genes in mites, demonstrating favorable efficacy and considerable potential for development. However, challenges remain, including poor environmental stability, slow action, high production costs, and insufficient understanding of their effects on non-target organisms. Therefore, future research should focus on the screening and development of novel bioactive substances of biological origin, elucidation of their mechanisms of action, optimization of formulation technologies, and assessment of their ecological safety. These efforts will provide valuable insights for promoting the advancement of bioactive substances and supporting sustainable agricultural development.

Key words Bioactive substances of biological origin, Spider mite control, RNA interference, Plant-derived active substances, Microorganism-derived active substances

0 Introduction

Spider mites (including *Tetranychus urticae*, *Tetranychus cinnabarinus*, *etc.*) are among the major pests in agricultural production[1]. They are characterized by polyphagy, broad host range, wide distribution, and rapid reproduction, and can infest a variety of plants such as vegetables, fruits, ornamental flowers, and grain crops. Fed on leaf sap, spider mites impair photosynthesis, leading to yellowing, wilting, and reduced yield and quality of crops. Additionally, their short life cycle and high reproductive capacity enable them to rapidly develop resistance to chemical acaricides, making their control increasingly challenging[2-3]. According to statistics, spider mite infestations cause annual economic losses totaling billions of dollars globally[4].

In recent years, although conventional chemical acaricides have played a certain role in controlling spider mites, several serious issues have emerged. For example, growing acaricide resistance has reduced the efficacy of available chemical treatments[5]. Moreover, the extensive use of these chemicals has raised concerns regarding environmental pollution, ecological imbalance, and harm to non-target organisms, drawing worldwide attention[6].

Against this backdrop, bioactive substances of biological origin have gained importance in mite management. These substances offer advantages such as wide availability, target specificity, minimal environmental impact, and low tendency to induce resistance, gradually positioning them as a promising direction for acaricide development[7]. Some plant-derived bioactive compounds can be optimized through extraction to obtain highly effective acaricidal components. Meanwhile, biological control methods, such as releasing predatory mites and other natural enemies, also represent feasible strategies that do not rely on synthetic chemicals. Both approaches enhance the diversity of mite control tactics, avoid environmental contamination, and contribute to sustainable agricultural pest management[8].

Recent years have witnessed significant progress in the development of plant-derived, microorganism-derived, and RNA interference (RNAi)-based bio-acaricides. These advances provide new ideas and tools for spider mite control. The development and utilization of biologically sourced active substances can not only reduce dependence on chemical acaricides and mitigate environmental pollution but also effectively delay resistance development, offering novel strategies and methods for the sustainable control of spider mites[9].

1 Current research status

1.1 Plant-derived active substances In recent years, the use of plant-derived active substances for controlling spider mites has developed rapidly. These substances are derived from a wide range of sources, are environmentally friendly, and are less likely to induce resistance, making them a leading trend in spider mite management[10-11]. The mechanism by which plant-derived active substances control spider mites primarily involves disrupting the nervous system or interfering with metabolic processes of the pests. For example, alkaloids such as veratramine found in extracts from Ve-

Received: August 2025 Accepted: October 29, 2025

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ratrum rhizomes can open voltage-gated sodium channels. The opening of these channels generates signals that subsequently activate voltage-activated calcium channels, leading to the release of neurotransmitters. This process ultimately causes tremors and convulsive shock in mites, resulting in death. In addition, Veratrum alkaloids can non-competitively inhibit acetylcholinesterase (AChE) in insects, further enhancing their acaricidal efficacy. The multi-site action of these compounds prevents mites from developing resistance through structural adaptations, underscoring their effectiveness in mite control[12].

1.2 RNAi technology RNA interference (RNAi) technology has also been increasingly applied in the control of spider mites. Its principle involves the specific silencing of key genes in mites, thereby disrupting their physiological metabolism and developmental processes, showing considerable potential for pest mite management[13]. For example, RNAi targeting the Retinoid X receptor 2 gene (TcRXR2) in *T. cinnabarinus* has been shown to affect egg hatching and development, leading to mite mortality. Plastid-mediated RNAi technology has also demonstrated high efficacy in controlling multiple species of spider mites. By specifically degrading mRNA of key mite genes, RNAi interferes with normal metabolic and developmental functions. Experimental studies have confirmed that RNAi can significantly increase egg mortality and inhibit the growth and development of adult mites. For instance, silencing TcRXR2 gene expression in *T. cinnabarinus* significantly reduced egg hatch rates, demonstrating notable effectiveness[14-16]. These findings indicate that RNAi technology holds great promise for the control of spider mites.

1.3 Microbial-derived active substances Microbial-derived active substances exhibit certain acaricidal effects against spider mites. The search for novel bioactive compounds from extremophiles, in particular, has become a topic of growing interest. These substances act by inhibiting the growth and reproduction of mite pests through microbial metabolites. For instance, Bacillus species demonstrate acaricidal activity against adult mites, nymphs, and larvae, and significantly suppress egg hatching. Moreover, by lysing adult mites and disrupting their development, such microbial agents can outperform conventional acaricides. Bacillus-based controls offer a novel mechanism of action, rapid efficacy, and a low risk of resistance development, effectively addressing the issue of pesticide resistance prevalent in current commercial acaricides[17]. Although research on microbial-derived active substances remains largely confined to laboratory settings and has not yet been widely applied in the field, studies have revealed that metabolites from extremotolerant microorganisms show promising mite suppression effects. These findings offer new directions for future spider mite control strategies[18-20].

2 Prospects

Despite the considerable potential of bioactive substances of biological origin in controlling spider mites, several challenges hinder their widespread adoption, including issues related to stability, persistence, speed of action, cost, and effects on non-target organisms. While technological innovations may help address these problems in future research, overcoming these barriers will require more in-depth investigation.

Natural bioactive substances are susceptible to environmental factors such as light, temperature, and humidity, leading to poor stability and inconsistent field performance. For example, some plant-derived active compounds degrade rapidly under sunlight, reducing their acaricidal activity. To enhance stability and prolong efficacy, technologies such as nano-formulations and microencapsulation can be applied to coat these substances, protecting the active ingredients from environmental degradation and enabling controlled release.

Furthermore, bioactive substances of biological origin often exhibit slower action and lower efficacy compared to conventional chemical acaricides. In field trials controlling two-spotted spider mites on strawberries, some bio-acaricides underperformed relative to their chemical counterparts. Therefore, optimizing formulation strategies and application methods, such as combining them with chemical pesticides, can not only improve efficacy but also mitigate resistance development.

The low potency and high production costs of many bioactive substances also limit their large-scale application. Complex extraction processes and high raw material costs for certain plant-derived compounds remain obstacles. Advancements in extraction technologies and the use of more sustainable raw materials could help reduce production costs.

In addition, some bioactive substances may have adverse effects on natural enemies and non-target insects. Selecting environmentally benign options, such as extracts from Veratrum rhizomes, can enhance ecological safety and reduce pesticide residues.

Existing studies demonstrate that bioactive substances of biological origin hold great promise for reducing reliance on chemical acaricides, minimizing environmental pollution, and delaying resistance development. Plant-derived compounds, RNAi technology, and microbial-based agents have all shown encouraging results in both laboratory and field trials. However, their mechanisms of action are not yet fully elucidated, and further research is needed to clarify multi-target effects, improve stability and persistence, and evaluate ecological safety.

In future, developing novel bioactive substances by exploring additional plant and microbial resources, and using synthetic biology to design new compounds with high acaricidal activity; elucidating mechanisms of action through molecular and physiological approaches to identify specific targets; conducting ecological safety assessments to evaluate impacts on non-target organisms and ecosystems, ensuring sustainable use. These steps will be crucial for advancing the practical application of bioactive substances in sustainable spider mite management.

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