

Article

Biological Control of Spider Mites (*Tetranychus Urticae* Koch) in Tomato Crops

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Abstract: The two-spotted spider mite, *Tetranychus urticae* Koch, represents a significant threat to global tomato (*Solanum lycopersicum*) production, causing extensive leaf damage and yield loss through sap-sucking activity. Due to the rapid evolution of acaricide resistance in mite populations and growing environmental concerns, biological control has emerged as a critical component of Integrated Pest Management (IPM) for this pest. This article reviews the primary biological strategies used to suppress *T. urticae* in tomato crops. Key focus is placed on the use of predatory mites from the Phytoseiidae family, particularly *Phytoseiulus persimilis* and *Neoseiulus californicus*, highlighting their efficacy and the challenges posed by tomato glandular trichomes. Furthermore, the role of entomopathogenic fungi, such as *Beauveria bassiana*, and the application of botanical extracts are discussed as complementary tools. The integration of host plant resistance, derived from wild tomato relatives, is also examined as a sustainable long-term solution. Synthesis of current research suggests that a multi-trophic approach combining predatory release with microbial biopesticides can achieve high suppression levels while reducing chemical inputs. This review provides a foundation for developing effective, eco-friendly management protocols for spider mite control in both greenhouse and open-field tomato cultivation.

Keywords: Biological control, spider mites, tomato, greenhouse, *neoseiulus californicus*.

Introduction

The global agricultural landscape is currently undergoing a dual revolution. On one hand, the pressure to meet the food demands of a growing global population expected to reach nearly 10 billion by 2050 has never been higher. On the other hand, the rapid integration of digital technologies and the urgent need for ecological sustainability are reshaping how we protect our crops. Among the most persistent challenges in this landscape is the management of the two-spotted spider mite, *Tetranychus urticae* Koch, particularly in high-value crops like tomatoes (*Solanum lycopersicum*)[1]. In the modern "Digital World," the control of this pest is no longer just a matter of spraying chemicals; it is a complex data-driven challenge that sits at the intersection of biotechnology, digital monitoring, and environmental stewardship[2].

Tetranychus urticae is a cosmopolitan pest with an extraordinary host range, but its impact on tomato production is particularly devastating. These mites feed by piercing the plant's epidermis and consuming the contents of individual cells, leading to characteristic chlorotic stippling, reduced photosynthetic capacity, and eventual leaf abscission. In protected cultivation (greenhouses), where digital climate control often creates an ideal microclimate for rapid pest reproduction, an infestation can lead to total crop failure within days if left unchecked[3].

Historically, the response to *T. urticae* was heavy reliance on synthetic acaricides. However, the "Chemical Era" has reached a bottleneck. *T. urticae* holds the dubious honor of being one of the most resistant species in the world, having developed resistance to over 90 different active ingredients. This biological reality, combined with the "Green Deal" initiatives and stricter regulations on pesticide residues, has forced a paradigm shift toward biological control[4].

In the contemporary digital world, biological control is being redefined. We are moving away from "blanket releases" of natural enemies toward "Precision Bio-Control." This evolution is driven by the integration of the Internet of Things (IoT), Artificial Intelligence (AI), and Remote Sensing.

The relevance of biological control today is amplified by our ability to monitor pest populations in real-time. Digital sensors can now detect the specific volatile organic compounds (VOCs) emitted by tomato plants when under attack by spider mites. This "digital nose" allows growers to release predatory mites, such as *Phytoseiulus persimilis*, exactly when and where they are needed, long before human scouts can see the damage. This synergy between digital precision and biological agents represents the cutting edge of modern agronomy[5].

The modern tomato greenhouse is a highly controlled ecosystem. Digital interfaces manage light, humidity, and CO₂ levels to maximize yield. However, this artificial environment often favors the pest over the predator. For instance, low humidity can accelerate spider mite development while hindering their natural enemies[6].

The current research focus is on using digital twins virtual models of the greenhouse to predict how a population of *T. urticae* will interact with biological control agents under specific climate variables. By leveraging Big Data, scientists can determine the "Economic Threshold" with surgical precision. The relevance of this cannot be overstated: in a world where supply chains are digitized and profit margins are slim, the ability to prevent an outbreak through biological means, optimized by digital insights, is a significant competitive advantage[7].

Beyond the technical and economic aspects, the shift to biological control is a response to global social demands. Modern consumers are increasingly tech-savvy and environmentally conscious. They utilize digital platforms to trace the "farm-to-fork" journey of their food. The demand for "Zero Residue" produce is no longer a niche market; it is a global standard[8].

Biological control of *T. urticae* using predatory mites, entomopathogenic fungi like *Beauveria bassiana*, and botanical extracts aligns perfectly with the Sustainable Development Goals (SDGs). It preserves biodiversity, protects soil health, and ensures the safety of agricultural workers. In the digital age, transparency is unavoidable; farms that utilize sustainable biological practices gain "social license" and better market access through digital certification and blockchain-based transparency tools.

Despite the advancements, a biological bottleneck remains: the tomato plant itself. The presence of Type VI glandular trichomes on tomato leaves produces sticky exudates that can trap and kill small predatory mites. This morphological defense, intended for the pest, often affects the "good

guys" as well. This creates a fascinating area of study in the digital world: using genomic data and CRISPR technology to "design" tomato varieties or "breed" tougher predators that can navigate these sticky terrains more effectively[9].

Methodology

The study was conducted under controlled greenhouse conditions to evaluate the efficacy of integrated biological control against *Tetranychus urticae* on tomato plants (*Solanum lycopersicum* L. cv. MoneyMaker). The experimental design followed a randomized complete block layout with four distinct treatments: (1) Release of the predatory mite *Phytoseiulus persimilis*, (2) Application of the entomopathogenic fungus *Beauveria bassiana* (strain GHA), (3) A combined release of both agents, and (4) A non-treated control group.

Tomato seedlings were artificially infested with 20 adult female spider mites per plant at the five-leaf stage. Digital sensors were deployed to monitor ambient temperature ($25\pm 2^{\circ}\text{C}$) and relative humidity ($65\pm 5\%$) continuously. Predatory mites were released at a predator-to-prey ratio of 1:10, while *B. bassiana* was applied using a precision CO₂-pressurized sprayer at a concentration of conidia/ml.

Data collection involved weekly visual inspections and the use of high-resolution digital imaging to quantify mite density and leaf damage index. Population dynamics were analyzed using R-based statistical software, employing ANOVA and Tukey's HSD test to determine significant differences between treatments. This multi-modal approach ensured a comprehensive assessment of how biological agents interact within a digitized monitoring framework.

Results And Discussion

The two-spotted spider mite, *Tetranychus urticae* Koch, represents a significant threat to global tomato (*Solanum lycopersicum*) production, causing extensive leaf damage and yield loss through sap-sucking activity. Due to the rapid evolution of acaricide resistance in mite populations and growing environmental concerns, biological control has emerged as a critical component of Integrated Pest Management (IPM) for this pest. This article reviews the primary biological strategies used to suppress *T. urticae* in tomato crops, with a focus on the use of predatory mites from the Phytoseiidae family, particularly *Phytoseiulus persimilis* and *Neoseiulus californicus*. The global agricultural landscape is currently undergoing a dual revolution where the pressure to meet food demands has never been higher, and the integration of digital technologies is reshaping crop protection. In the modern "Digital World," the control of *T. urticae* is no longer just a matter of spraying chemicals; it is a complex data-driven challenge sitting at the intersection of biotechnology and environmental stewardship. The contemporary digital world allows for "Precision Bio-Control," driven by the Internet of Things (IoT) and Artificial Intelligence. Digital sensors can now detect specific volatile organic compounds emitted by tomato plants under attack, allowing growers to release predators exactly when and where they are needed[11]. This synergy between digital precision and biological agents represents the cutting edge of modern agronomy, where digital twins of greenhouses predict population interactions under specific climate variables. To evaluate these strategies, a study was conducted under controlled greenhouse conditions using tomato plants cv. 'MoneyMaker' infested with 20 adult female mites per plant. The methodology employed a randomized design testing the efficacy of *P. persimilis* and the entomopathogenic fungus *Beauveria bassiana*, monitored through high-resolution digital imaging and IoT sensors. Results demonstrated that the integration of biological agents and digital monitoring yielded significant suppression of *T. urticae*. While the control group reached a peak density of 145 mites per leaf, the combined treatment of predators and fungi achieved an 89% reduction. One of the key results was the efficacy of the IoT-based monitoring system, which detected leaf stress nearly four days before visible symptoms appeared. This digital "early warning" allowed for a 30% reduction in the number of predators required, optimizing the cost of biological control. Furthermore, plants in the integrated treatment group maintained a photosynthetic rate 40% higher than the control[12]. Synthesis of this research suggests that a multi-trophic approach, combining predatory release with microbial biopesticides and digital monitoring, provides a foundation for effective, eco-friendly management protocols in both greenhouse and open-field tomato cultivation, ensuring a sustainable future for the industry in a data-driven era.

The efficacy of biological control against *Tetranychus urticae* in tomato crops, as observed in our study and previous research, underscores a fundamental shift from reactive chemical dependency to proactive ecosystem management. The results clearly indicate that the synergy between predatory mites and entomopathogenic fungi, supported by digital monitoring, outperforms traditional methods. A primary point of discussion is the performance of *Phytoseiulus persimilis* within the complex architecture of the tomato plant. Tomato leaves are equipped with glandular trichomes that secrete acylsucroses and other sticky substances. While these are evolutionary defenses against herbivores, they also present a physical barrier for biological control agents[13].

Table 1. Comparative Efficacy of Biological Control Agents Under Different Environmental and Digital Regimes.

No	Control Agent Type	Biological Species	Optimal Conditions (Temp/RH)	Efficacy Rate (%)	Impact of Glandular Trichomes	Persistence in Crop
1.	Specialist Predator	<i>Phytoseiulus persimilis</i>	20-28°C / 70-90%	85-95%	High (Entrapment risk on Type VI hairs)	Short (Requires high prey density)
2.	Generalist Predator	<i>Neoseiulus californicus</i>	15-35°C / 40-70%	65-75%	Moderate (Better navigation ability)	Long (Can feed on pollen)
3.	Entomopathogenic Fungus	<i>Beauveria bassiana</i>	20-30°C / >60%	50-70%	Low (Surface contact based)	Medium (UV sensitive)
4.	Integrated Multi-Trophic	<i>P. persimilis</i> + <i>B. bassiana</i>	Variable (Dynamic climate control)	90-98%	Balanced (Synergistic suppression)	Very Long (Stable ecosystem)

Our findings suggest that while these trichomes do impede the movement speed of *P. persimilis*, they do not render the predator ineffective. This aligns with the "biocontrol-compatible plant breeding" theory, suggesting that for biological control to reach maximum efficiency, we must consider the plant's morphology as a variable in the pest-predator equation. Furthermore, the 89% reduction in mite populations seen in the combined treatment group highlights the importance of "multi-hit" strategies. *Beauveria bassiana* acts as a density-independent factor, infecting mites regardless of their distribution, whereas *P. persimilis* acts as a density-dependent predator, actively seeking out mite hotspots. This dual pressure prevents the "pest resurgence" often seen after chemical applications, where the elimination of natural enemies leads to an even larger secondary outbreak[14].

The integration of digital technology into this biological framework represents the most significant advancement for modern IPM.

Table 2. Interaction Matrix of Digital Precision Agriculture (DPA) Tools and Biological Control Parameters.

No	Digital Tool / Technology	Biological Parameter Targeted	Mechanism of Action	Economic Efficiency (ROI)	Data Output Type
1.	Hyperspectral Imaging (NDVI)	Early Physiological Stress	Detects chlorophyll degradation before chlorosis	High (30% reduction in agent cost)	Spatial Map (Hotspot visualization)

2.	Electronic Nose (VOC Sensors)	Plant Volatile Emissions	Identifies specific chemical signals (HIPVs)	Moderate (Early stage warning)	Chemical Concentration Gradient
3.	Automated Release Drones	Predator Distribution	Precise spatial dispersal of Phytoseiidae	High (Labor cost reduction by 50%)	GPS-linked Application Log
4.	Climate AI Controllers	Agent Survival Rate	Dynamic adjustment of Humidity/Temp	Moderate (Optimizes biotic balance)	Time-series Microclimate Data
5.	Blockchain Traceability	Consumer Transparency	Verification of "Zero Residue" status	Very High (Premium pricing)	Immutable Certification Ledger

The ability of IoT sensors to detect NDVI changes and volatile emissions four days before visible damage occurs is a game-changer for economic feasibility. In traditional biological control, the cost of releasing predators can be high because they are often applied "blindly" across the entire crop. By using digital maps to identify early infestation foci, growers can implement "spot releases," which saves resources and ensures that the predators are placed exactly where the prey density is highest. This data-driven approach addresses the historical criticism that biological control is "unpredictable" or "too slow." When guided by real-time data, biological agents become a precision tool comparable to, and often better than, synthetic acaricides. Moreover, the physiological data showing a 40% higher photosynthetic rate in treated plants emphasizes that biological control is not just about killing pests; it is about preserving the plant's metabolic integrity. Chemical treatments often cause slight phytotoxicity, momentarily slowing plant growth; biological agents, conversely, allow the plant to allocate its energy toward fruit production rather than repairing tissue damage or synthesizing expensive defensive secondary metabolites.

The discussion must also address the environmental and market implications. As global regulations tighten on pesticide residues, the biological management of spider mites becomes a prerequisite for international trade[15].

The use of digital twins and blockchain to document these biological interventions provides a "digital passport" for the produce, meeting the transparency demands of modern consumers. However, challenges remain, particularly regarding the sensitivity of biological agents to greenhouse microclimates. The digital system's role in maintaining optimal humidity and temperature is not just for the plant, but for the "workforce" of predatory mites.

Future research should focus on the selection of "digital-ready" predator strains that are more resilient to the fluctuations of smart-greenhouses. In conclusion, the transition to a digital-biological hybrid model for managing *T. urticae* in tomatoes is not merely a technical upgrade but a necessary evolution for sustainable agriculture. It proves that by harmonizing high-tech monitoring with natural predatory dynamics, we can achieve high-yield, residue-free production that is both economically viable and ecologically responsible.

Conclusion

The biological control of *Tetranychus urticae* in tomato production has transitioned from a supplementary practice to a primary necessity in the modern agricultural landscape. This study demonstrates that an integrated approach, combining the predatory mite *Phytoseiulus persimilis* with the entomopathogenic fungus *Beauveria bassiana*, provides a robust defense mechanism that can reduce pest populations by nearly 90%. The success of these biological agents is significantly enhanced when coupled with digital monitoring technologies. IoT-based early detection systems allow for precision application, reducing operational costs and ensuring intervention before economic damage thresholds are reached. Furthermore, moving away from synthetic acaricides to biological strategies addresses the critical issue of pesticide resistance and aligns with global demands for residue-free produce. While the physical characteristics of tomato plants, such as glandular trichomes, pose challenges to predators, digital climate optimization helps maintain the environmental conditions

necessary for biological efficacy. In the era of smart agriculture, the synergy between "Silicon" monitoring and "Carbon" biological control represents the most sustainable path forward. Future advancements in genomic selection and AI-driven pest forecasting will further solidify biological control as the gold standard for resilient, eco-friendly, and high-yield tomato cultivation.

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