Mahmood SU *et al*. (2024)
Notulae Botanicae Horti Agrobotanici Cluj-Napoca
Volume 52, Issue 3, Article number 13781
DOI:10.15835/nbha52313781
Review Article

Eriophyid mites in fruit crops: Biology, ecology, molecular aspects, and innovative control strategies

Syed U. MAHMOOD[1], Runqian MAO[1], Inzamam UL HAQ[2], Xiaoduan FANG[1*]

[1]*Institute of Zoology, Guangdong Academy of Sciences, Guangdong Key Laboratory of Animal Conservation and Resource Utilization, Guangdong Public Laboratory of Wild Animal Conservation and Utilization, Guangzhou, Guangdong 510260, China; syedusmanmahmood3@gmail.com; maorun@giz.gd.cn; fangxiaoduan@163.com (*corresponding author)*
[2]*Fujian Agriculture and Forestry University, State Key Laboratory of Ecological Pest Control for Fujian and Taiwan Crops, Fuzhou, China; enzyuaf@gmail.com*

Abstract

Eriophyid mites, minute arachnids within the family Eriophyidae, pose significant threats to fruit crops globally, leading to substantial economic losses in agriculture. This comprehensive review aims to elucidate the intricate biology, ecology, molecular aspects, and innovative control strategies of these pervasive pests. Eriophyid mites exhibit a complex life cycle and reproductive strategy, with their habitat preferences and distribution heavily influenced by environmental factors and host-plant interactions. Advances in molecular biology have provided more profound insights into their genetics and interactions at the molecular level, revealing crucial information for developing targeted pest management strategies. Control strategies for eriophyid mites encompass chemical methods, such as applying acaricides and understanding resistance mechanisms, as well as biological control using natural predators and parasitoids. Cultural and physical control methods, including crop rotation and mechanical removal, play vital roles in integrated pest management (IPM). Emerging approaches like RNA interference (RNAi) and semiochemical-based controls offer promising alternatives for sustainable pest management. This review underscores the importance of a multifaceted approach to effectively manage eriophyid mite infestations, integrating traditional and novel strategies. Future research should focus on overcoming current challenges, enhancing the efficacy of control methods, and further exploring the molecular mechanisms underlying mite-plant interactions.

Keywords: chemical ecology; eriophyid mite; fruit crop pest; integrated pest management; molecular aspects

Introduction

Eriophyid mites, minute arachnids belonging to the family Eriophyidae, have emerged as formidable agricultural adversaries due to their subtle yet pervasive influence on fruit crops. These minuscule pests, often measuring less than 0.2 millimeters, impact fruit crop health and productivity (Jeppson *et al*., 1975; Vidović *et al*., 2023). With a vast range of host plants spanning diverse ecosystems, they have become a ubiquitous concern for fruit growers globally (Navia *et al*., 2013; Zhao *et al*., 2018). The importance of eriophyid mites in the

Received: 15 Mar 2024. Received in revised form: 20 May 2024. Accepted: 24 Jul 2024. Published online: 09 Sep 2024.
From Volume 49, Issue 1, 2021, Notulae Botanicae Horti Agrobotanici Cluj-Napoca journal uses article numbers in place of the traditional method of continuous pagination through the volume. The journal will continue to appear quarterly, as before, with four annual numbers.

context of fruit crop agriculture cannot be overstated. These tiny, sap-sucking arachnids inflict damage by puncturing plant cells and extracting cell contents, resulting in various physiological disruptions, including leaf curling, gall formation, and reduced photosynthesis (Skoracka *et al*., 2010; Hajizadeh and Hosseini, 2023a). Beyond direct feeding damage, they can serve as vectors for plant pathogens, compounding the threat they pose to fruit crops (Lindquist, 1996; Hajizadeh and Hosseini, 2023b). Consequently, understanding the intricate dynamics of eriophyid mites is paramount for maintaining fruit crop health and ensuring food security. The purpose of this comprehensive review is to unravel the complex tapestry of eriophyid mite biology, ecology, and innovative control strategies. The ever-increasing globalization of agriculture necessitates a proactive approach to pest management. Recent estimates suggest that eriophyid mites cause annual losses of approximately $500 million to the global fruit crop industry, underscoring the economic importance of effective management strategies (Hoffmann, 2004)(Figure 1). This review aims to bridge the gap between microscopic pests and global agricultural concerns, providing a comprehensive resource for researchers, growers, and stakeholders alike as they grapple with the multifaceted challenges posed by eriophyid mites.

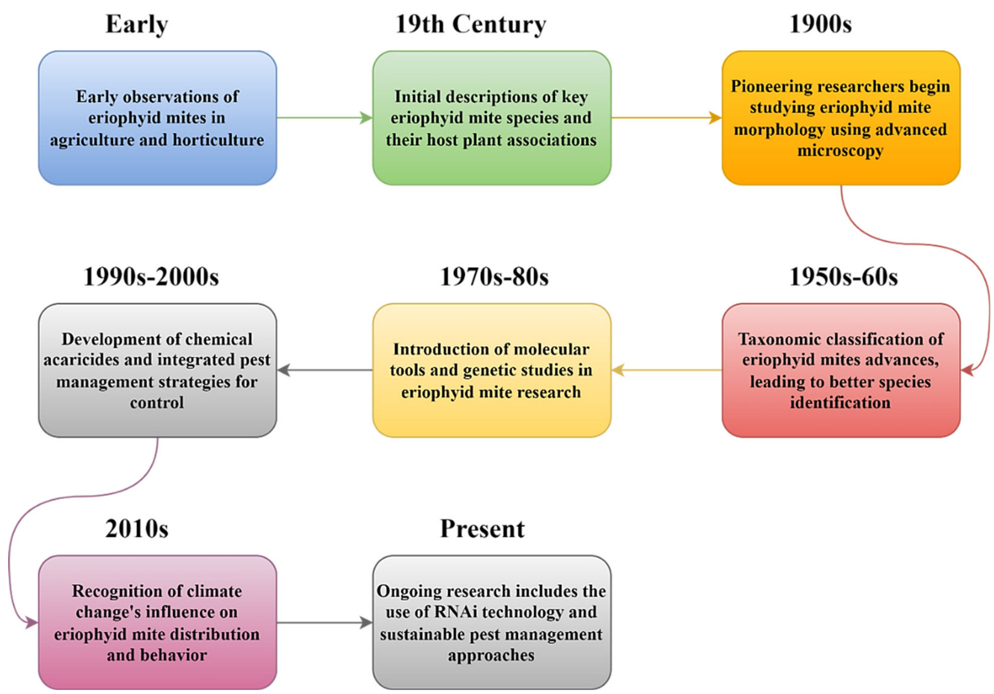

Figure 1. Historical Development of Research on Eriophyid Mites. This figure illustrates key milestones such as identifying eriophyid mites as significant pests in 1975, the development of the first chemical controls in the 1980s, and recent advances in molecular research in the 2010s. Each milestone marks a critical advancement in understanding and managing these pests, highlighting the ongoing evolution of pest control methodologies

Importance of citrus rust mites and fruit rust mites in agriculture

The agricultural community has shown considerable interest in the impact of citrus rust mites (such as *Phyllocoptruta oleivora* and *Aculops pelekassi*) and fruit rust mites (found in various genera within Eriophyidae) on fruit crops. These minuscule arachnids are widely recognized for their capacity to inflict significant economic damage by impairing the overall health and productivity of various fruit-bearing plants (Maity and Mondal, 2023). Citrus crops, such as oranges, grapefruits, lemons, and mandarins, play a crucial role in the agricultural industry worldwide, serving as a significant source of income for farmers and contributing to the global food supply chain. Citrus rust mites, *P. oleivora*, exhibit a distinct preference for citrus trees, hence inducing harm by consuming the plant's epidermal cells (Demard and Qureshi, 2023). The act of feeding by certain organisms results in the development of distinct silvering or bronzing of the leaves, which ultimately hampers the tree's photosynthetic ability and inhibits the growth of fruits (Childers *et al*., 1996). The economic ramifications resulting from infestations of citrus rust mites are significant. Fruit crops that are damaged by these mites see a reduction in both the quality and quantity of their produce, negatively impacting market value and overall profitability (Jeppson *et al*., 1975).

Likewise, fruit rust mites from the Eriophyidae family demonstrate their capacity to cause damage across various fruit crops. These pests can establish colonies on a range of hosts, such as apple trees, pear trees, and grapevines, exacerbating the global difficulties encountered by fruit cultivators. The feeding behaviors of these insects result in the development of galls, leaf curls, and other abnormalities in fruit trees, causing disruptions to their regular physiological processes (George *et al*., 2022; Lindquist, 1996). As mentioned earlier, the modifications result in diminished fruit quality, decreased production, and heightened vulnerability to secondary diseases, placing a significant financial burden on cultivators and the agricultural sector at large (Abdel Ghani *et al*., 2022)—moreover, the significance of these mites beyond the immediate agricultural harm they inflict. Eriophyid mites, such as citrus rust mites, can serve as carriers for a range of plant infections, bringing illnesses that exacerbate the negative impact on crop yields (Navia *et al*., 2013). The indirect consequences of eriophyid mite infestations in agricultural systems enhance the importance of implementing comprehensive approaches for pest control.

Key species of citrus rust mites and other fruit rust mites

Several significant citrus rust mites (*Phyllocoptruta oleivora*, *Aculops pelekassi*) and fruit rust mites (various genera within Eriophyidae) have been identified within the family Eriophyidae. These mites possess distinct characteristics and exhibit host preferences that are of agricultural importance.

Citrus rust mites

Phyllocoptruta oleivora: *P. oleivora*, often recognized as the citrus rust mite, holds a prominent position within the citrus rust mite population and is of considerable economic importance. The primary host plants of this pest are citrus trees, specifically oranges, grapefruits, lemons, and mandarins. The feeding behaviors exhibited by *P. oleivora* lead to several forms of damage, such as leaf silvering or bronzing, leaf curling, and the production of galls (Childers *et al*., 1996). The visual symptoms seen serve as indicators of the existence of these factors and emphasize their significant influence on citrus output (Dousseau *et al*., 2023).

Aculops pelekassi: *A. pelekassi* exhibits a particular preference for the leaves and fruit of citrus trees, resulting in the deformation of leaves and a bronzing effect. These symptoms can negatively impact the quality and quantity of fruit produced (Childers *et al*., 1996). The small range of hosts and unique indications of damage exhibited by *A. pelekassi* render it a topic of specific significance within the field of citrus pest management (Tsuchida *et a*l., 2022).

Fruit rust mites

Within the broader category of fruit rust mites, numerous species encompass various genera within the Eriophyidae family. These mites exhibit host specificity, often infesting specific fruit crops and causing characteristic damage. Some key examples include:

Aceria spp.: The taxonomic classification *Aceria* encompasses a diverse assemblage of organisms that exhibit parasitic behavior on various fruit-bearing plants, such as apple trees, pear trees, and strawberry plants (Buttachon *et al*., 2022). *Aceria* mites are recognized for their ability to elicit the development of galls on leaves and fruit, resulting in morphological abnormalities and diminished fruit characteristics (Aghazadeh *et al*., 2023; Skoracka *et al*., 2010).

Calepitrimerus spp.: *Calepitrimerus* mites are closely linked with grapevines, resulting in leaf deformation and subsequent destruction (Xue and Liu, 2022). The impact of grapevine leaf health and vineyard output makes them particularly significant in viticulture (Liu *et al*., 2022).

The species mentioned above serve as a subset of the overall diversity observed within the Eriophyidae family, thus emphasizing the significance of precise species identification and categorization to facilitate efficient pest control strategies. To design effective control techniques and minimize the impact of these species on fruit crops, it is crucial to comprehend the unique attributes, host preferences, and patterns of harm associated with these organisms.

Purpose and scope of the review

This comprehensive review aims to elucidate the complex realm of citrus and fruit rust mites and their wider ramifications within the agricultural domain. This review seeks to offer a thorough understanding of these little yet impactful arachnids by thoroughly analyzing their taxonomy, ecology, biology, global distribution, and new control measures. This review aims to comprehensively explore many aspects of eriophyid mite research, spanning a broad scope. The primary focus of this study is to examine the wide range of variety within this family and to identify the important species that are particularly relevant to fruit crops. Applying a phylogenetic lens allows for determining the evolutionary relationships among these pests, establishing a basis for subsequent investigation. Exploring the ecological domain encompasses the examination of habitat preferences and interactions with host plants exhibited by citrus rust mites and fruit rust mites. This study investigates the chemical cues that influence the behavior of organisms, providing insights into their complex ecological functions. An in-depth analysis of the life cycles, feeding behaviors, physical traits, and genetic makeup of these organisms enhances our comprehension of their biological properties and population dynamics. The global distribution patterns of eriophyid mites have been revealed, shedding light on their geographic dispersion and the factors that impact their distribution, including climate change. Molecular investigations provide an avenue to explore the genetic variety of these organisms, thereby elucidating the underlying mechanisms that govern their interactions with host plants.

This review aims to investigate several tactics utilized in the field of pest management to limit damage caused by eriophyid mites. These strategies encompass a range of approaches, including chemical, biological, cultural, and integrated control methods. This study aims to analyze resistance mechanisms and develop techniques, providing valuable insights into the ongoing conflict between growers and these microscopic foes. The practicality and success of these solutions will be shown through real-world case studies, which will extract essential lessons for fruit producers and researchers. In addition, we will explore the various challenges posed by increasing threats, identify areas of study that require further investigation, and examine potential innovative approaches to the management of eriophyid mites. Considering the changing landscape of global agriculture, this comprehensive assessment serves as an essential reference for stakeholders and scholars alike. It offers valuable insights and guidance on the implementation of sustainable pest control strategies specifically tailored to fruit crops. The focus of this study is the range of eriophyid mites, spanning from the microscopic level to the broader agricultural context. This review aims to bridge the existing knowledge divide between these minuscule pests and the multifaceted issues they present in relation to the health and productivity of fruit crops on a worldwide scale.

Biology of Eriophyid Mites

Reproduction and life cycle

The reproduction and life cycle of eriophyid mites are remarkable processes that adapt them to their unique ecological niches and influence their population dynamics. Understanding these intricacies is essential for developing targeted pest management strategies and appreciating their roles in ecosystems.

Reproduction

Eriophyid mites employ a range of reproductive strategies that are tightly intertwined with their host plants and the surrounding environment. Many eriophyid mite species predominantly reproduce asexually through a process known as parthenogenesis (Amrine Jr *et al*., 2003; Salazar-Fillippo et *al*., 2022; Pournajafi *et al*., 2023). In parthenogenesis, females produce offspring without fertilization, resulting in genetically identical daughters. This reproductive strategy enables rapid population growth, particularly when conditions are favorable. Sexual reproduction also occurs in some eriophyid mite species, typically in response to environmental cues or changing conditions (Pournajafi *et al*., 2023). Males and females engage in mating behaviors facilitated by pheromones, ultimately leading to the production of fertilized eggs (Wei *et al*., 2023).

Life cycle

The life cycle of eriophyid mites is often closely tied to their host plants and local environmental conditions:

The life cycle of eriophyid mites is a captivating journey that starts with the deposition of eggs onto host plant tissues (Figure 2). The timing and location of egg laying can vary due to factors like the suitability of the host plant and temperature (Shatrov and Kudryashova, 2006; Seeman and Walter, 2023). These tiny mites then hatch from the eggs as larvae with three pairs of legs. They are incredibly mobile during this stage, using specialized mouthparts to feed on plant cells. After the larval stage, they go through two nymphal stages, the protonymph and tritonymph, and with each stage, they gain extra pairs of legs, making them more adept at interacting with their host plants (Shatrov and Kudryashova, 2006; Seeman and Walter, 2023). Eventually, they mature into the adult stage, recognized by their four pairs of legs. The adults take on essential roles in the mite population, such as feeding, mating, and kickstarting the next generation (Shatrov and Kudryashova, 2006; Seeman and Walter, 2023). Understanding these stages is vital for grasping the dynamics of eriophyid mite populations and for coming up with effective strategies to curb their impact on crops.

Host plant influence

Host plants play a pivotal role in the reproduction and life cycle of eriophyid mites. Mite development, behavior, and population dynamics are intricately linked to host plant physiology and the availability of suitable tissues for feeding and reproduction (Huszar, 2023).

Environmental factors

Environmental factors such as temperature, humidity, and seasonal changes can profoundly impact the timing and success of eriophyid mite reproduction (Yin et al., 2023). These factors influence developmental rates, diapause (a state of dormancy), and the synchronization of life cycle stages.

A blend of asexual and sexual reproductive strategies, environmental cues, and host-plant interactions shapes the reproduction and life cycle of eriophyid mites. These intricacies underscore the adaptability and resilience of eriophyid mites within their specific ecological niches.

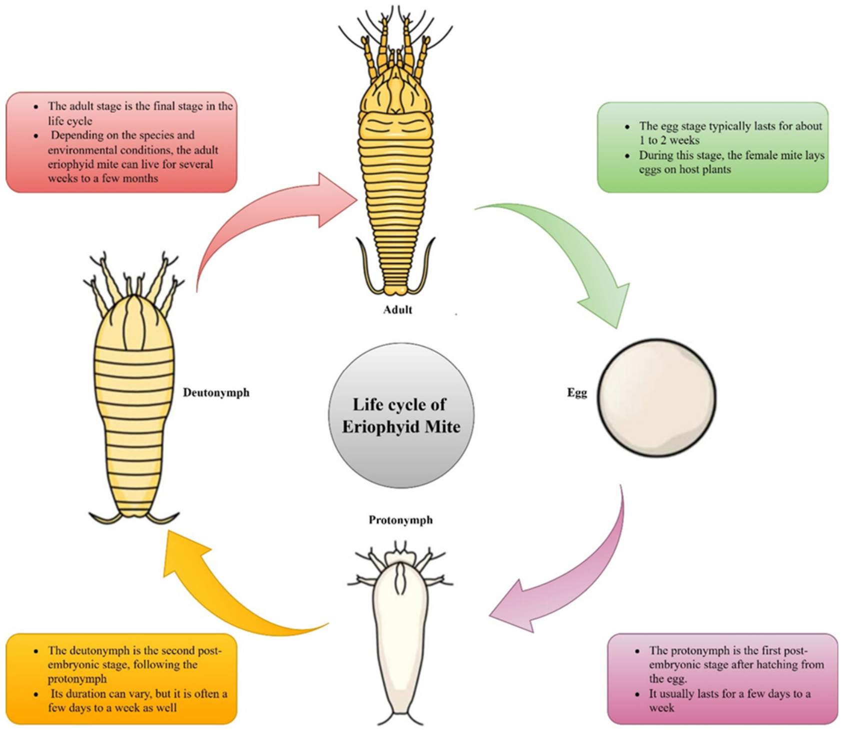

Figure 2. Life cycle of eriophyid mites. This figure depicts the complete life cycle stages of eriophyid mites, including egg, nymph (protonymph and tritonymph), and adult stages. Each stage is characterized by specific behaviors and physical adaptations that enable the mites to thrive on their host plants

Overwintering strategies

Overwintering strategies are critical adaptations for eriophyid mites to endure adverse environmental conditions and persist through seasons. These strategies enable their survival during periods when host plants may not be readily available or when environmental conditions are less favorable for active life stages (Lotfollahi, Mehri-Heyran *et al*., 2023).

Diapause

Diapause is a prominent overwintering strategy employed by many eriophyid mite species (Amini *et al*., 2023). Diapause is a state of dormancy characterized by reduced metabolic activity and minimal movement. It allows mites to conserve energy and withstand unfavorable conditions, such as low temperatures and reduced humidity.

Induction Factors: Diapause induction is often triggered by environmental cues, particularly decreasing day length and temperature (Desnitskiy *et al*., 2023). As these conditions signal the approach of winter, eriophyid mites enter diapause to escape harsh conditions.

Protective Structures: During diapause, eriophyid mites may seek refuge in protective microenvironments, such as crevices in plant bark or leaf litter, to shield themselves from extreme temperatures and desiccation (Yin *et al*., 2023).

Life stage selection

Eriophyid mites often select specific life stages for overwintering. For example:

Egg Overwintering: In some species, eggs are particularly resilient to adverse conditions and may be the stage chosen for overwintering (Joshi *et al*., 2023). This allows the mites to ensure the survival of their offspring in anticipation of more favorable conditions in the spring.

Adult Overwintering: In contrast, adult eriophyid mites of certain species may exhibit adaptations that enable them to withstand winter conditions (Lotfollahi, Mehri-Heyran *et al*., 2023). These adaptations may include cuticular modifications that enhance resistance to desiccation.

Host plant and microhabitat selection

Eriophyid mites often select specific host plants and microhabitats for overwintering (Shanovich *et al.*, 2023). These choices are influenced by factors such as the suitability of host plants for diapause and the presence of protective features within the host plant environment.

Plant Bud Galleries: Some eriophyid mites create bud galls on host plants, which serve as protective enclosures for overwintering mites (Pirithiraj and Soundararajan, 2023). Within these galls, mites find refuge from external conditions and access to plant tissues.

Leaf Litter and Bark: Mites may also overwinter in leaf litter or bark crevices near host plants (Ermilov *et al*., 2023). These microenvironments provide insulation and protection against temperature fluctuations.

Eriophyid mites employ various overwintering strategies, with diapause being a common and vital adaptation. The selection of life stages, host plants, and microhabitats for overwintering is influenced by environmental cues and the mite species' specific ecological requirements. These strategies enable eriophyid mites to endure harsh winter conditions and emerge in spring to continue their life cycle.

Ecology and Behavior

Habitat preferences

Eriophyid mites exhibit a remarkable diversity of habitat preferences, including unexpected environments such as urban green spaces and high-altitude regions. For instance, a recent study found that the citrus rust mite (*Phyllocoptruta oleivora*) can thrive in non-traditional habitats like rooftop gardens, which presents new challenges for control strategies (Navia *et al*., 2009)(Table 1). The primary habitat for these mites is the phylloplane, the surface of plant leaves, where they feed by piercing plant cells and extracting cell contents (Amrine Jr *et al*., 2003; Bilki *et al*., 2022). This intimate association with the phylloplane underscores their vulnerability to environmental conditions, particularly moisture levels. Eriophyid mites are highly sensitive to desiccation and thrive in environments with high humidity (Alkathiry *et al*., 2022; Jeppson *et al.*, 1975).

Table 1. Habitat preferences and distribution of key eriophyid mite species

Species	Preferred host plants	Geographical distribution	References
Phyllocoptruta oleivora	sweet orange, lemon, mandarin, grapefruit	North and South America, Europe, Asia, Africa	(Childers *et al*., 1996; Jeppson *et al*., 1975)
Eriophyes pyri	apple, pear, cherry	North America, Europe, Asia	(Furmanczyk *et al*., 2022; Lotfollahi *et al*., 2023; Moskalets *et al*., 2022)
Aculus schlechtendali	walnut, hickory, pecan	North America	(Silva *et al*., 2022)
Aceria tulipae	various wild and cultivated plants (including tulips)	Worldwide, temperate regions	(Gope *et al*., 2022; Hamza *et al*., 2023; Luong, 2022)
Phyllocoptes citri	citrus (orange, lemon, lime)	Mediterranean region, Middle East, North America	(Jia *et al*., 2023; Z hang *et al*., 2022)
Aculus cornutus	various grasses and cereal crops	Europe, North America	(Rueda-Ramírez *et al*., 2022)

One of the most distinctive features of eriophyid mites is their host specificity. Many eriophyid mite species are highly specialized, infesting specific plant species or genera (Skoracka *et al*., 2010). Their host plant associations are often so precise that they can be used as key diagnostic characteristics for species identification. These host-specific relationships have significant implications for agriculture, as eriophyid mites can cause damage to economically important crops within their preferred host range.

Distribution patterns

Eriophyid mites exhibit diverse distribution patterns influenced by factors such as host plant availability, climate, and geographic barriers. Their distribution may be localized, regional, or even global, depending on the species. Climate plays a pivotal role in determining distribution, as eriophyid mites are highly sensitive to temperature and humidity (Li *et al*., 2023; Skoracka *et al*., 2010). Climate change has the potential to alter their distribution patterns, affecting fruit crop ecosystems (Table 2).

Moreover, their distribution is intricately linked to host plant availability. Eriophyid mites rely on host plants for sustenance and reproduction. Therefore, the presence and distribution of suitable host plants directly influence the distribution of eriophyid mite populations (Childers *et al*., 1996). The habitat preferences and distribution patterns of eriophyid mites are shaped by their dependence on host plants, sensitivity to environmental conditions, and evolutionary history. Understanding these ecological dynamics is essential for devising targeted pest management strategies and predicting the impact of climate change on eriophyid mite populations.

Table 2. Impact of climate change on eriophyid mite distribution

Eriophyid mite species	Temperature impact	Precipitation impact	Geographic range changes	References
Phyllocoptruta oleivora	warmer temperatures favor a wider distribution	high humidity levels are conducive to mite survival and reproduction	North and South America, Europe, Asia, Africa	(Demard and Qureshi, 2020)
Eriophyes pyri	expansion into cooler regions	increased survival in drier conditions	Northward range expansion in Europe and Asia	(Furmanczyk *et al*., 2022; Lotfollahi *et al*., 2023)
Aculus schlechtendali	Northward range expansion	N/A	Spread to new northern regions in North America	(Silva *et al*., 2022)
Aceria tulipae	Range expansion in cooler regions; earlier emergence	Favorable conditions for reproduction due to milder	Extension into higher latitudes in temperate regions	(Gope *et al*., 2022; Luong, 2022)
Phyllocoptes citri	The northward shift of the distribution	N/A	Extended range in northern regions and more frequent infestations	(Jia *et al*., 2023)
Aculus cornutus	N/A	N/A	Limited studies; potential impacts on distribution uncertain	(Rueda-Ramírez *et al*., 2022)

Host plant interactions

Host plant interactions are a cornerstone of the ecology and behavior of eriophyid mites, profoundly influencing their distribution, feeding behavior, and reproductive strategies (Bizzarri *et al*., 2022). Understanding these intricate relationships is pivotal for effective pest management and elucidating the ecological roles of these tiny arachnids.

Host specificity

Eriophyid mites are renowned for their exceptional host specificity. Many species have evolved to infest particular plant species or genera exclusively (Skoracka *et al*., 2010). This level of specialization is reflected in their common names, which often reference their preferred host plants. For example, the citrus rust mite (*Phyllocoptruta oleivora*) specifically targets citrus trees, while the apple rust mite (*Aculus schlechtendali*) infests apple trees (Villacis-Perez *et al*., 2022). This host specificity has significant implications for agriculture, as it dictates which crops are susceptible to eriophyid mite damage (Table 3).

Table 3. Feeding habits and damage caused by different eriophyid mite species on various host plants

Mite species	Preferred host plants	Feeding habits	Damage type	Affected plant parts	References
Phyllocoptruta oleivora	sweet Orange, Lemon, Mandarin, Grapefruit	cell contents	leaf discoloration and fruit blemishes	leaves, fruit	(Demard et al., 2023)
Eriophyes pyri	apple, pear, cherry	cell-content extraction	blister-like galls	leaves, buds	(Brewer et al., 2018; Quaintance, 1912)
Aculus schlechtendali	walnut, hickory, pecan	cell-content extraction	leaf blistering	leaves, buds	(Duso et al., 2010; Lotfollahi, Mehri-Heyran, et al., 2023)
Aceria tulipae	various wild and cultivated plants (including tulips)	cell-content extraction	leaf curling	leaves	(Beltran, 2020)
Phyllocoptes citri	citrus (orange, lemon, lime)	cell-content extraction	gall formation	leaves, buds, fruits	(Jia et al., 2023)
Aculus cornutus	various grasses and cereal crops	cell-content extraction	leaf curling	leaves	(Schmidt-Jeffris et al., 2019)

Feeding behavior

Eriophyid mites feed on plant tissue by puncturing plant cells and extracting cell contents through their specialized mouthparts, called stylets (Amrine Jr *et al*., 2003; Hamdi *et al*., 2023). Their feeding behavior can lead to various physiological disruptions in host plants, including leaf curling, gall formation, and silvering or bronzing of leaves (Childers *et al*., 1996). These alterations in plant morphology and physiology are often used as diagnostic symptoms of eriophyid mite infestations.

Gall formation

One particularly notable aspect of eriophyid mite-host plant interactions is gall formation. Many eriophyid mite species induce the development of galls on host plants. Galls are abnormal growths or structures formed by the plant in response to mite feeding (Desnitskiy *et al.*, 2023). These galls serve as protective enclosures for mite colonies, providing shelter and a nutrient-rich environment (Skoracka *et al.*, 2010). The formation of galls can have both detrimental and beneficial effects on host plants, depending on the species involved.

Role in disease transmission

Eriophyid mites can also act as vectors for plant pathogens. Their feeding behavior may introduce viruses or other pathogens into host plants, facilitating the spread of diseases (Lindquist, 1996). This indirect impact further underscores the importance of understanding eriophyid mite-host plant interactions in the context of crop health and disease management. Eriophyid mites' host-plant interactions are pivotal components of their ecology and behavior (Song *et al*., 2023). Their remarkable host specificity, feeding behavior, gall-inducing activities, and potential role in disease transmission shape their ecological roles within agricultural ecosystems. By unravelling the complexities of these interactions, researchers and growers can develop more targeted and sustainable pest management strategies.

Chemical ecology

Pheromones

Pheromones, a subset of semiochemicals, are chemical substances released into the environment by eriophyid mites to convey vital information to conspecifics. These compounds play multifaceted roles within mite populations, guiding behavior and fostering reproductive success:

Mating pheromones are instrumental in mate recognition and courtship behaviors (Amrine Jr *et al*., 2003; Pfingstl and Kerschbaumer, 2022). They enable individuals to distinguish between potential mates, ensuring reproductive compatibility. These chemical cues orchestrate the delicate dance of courtship, leading to successful copulation and the continuation of the species. Aggregation pheromones promote the clustering of mites on host plants, facilitating the formation of colonies (Amrine Jr *et al*., 2003; Masier *et al*., 2023). These communal gatherings offer advantages such as increased protection from environmental stresses and resource sharing. Aggregation pheromones foster cooperative behaviors essential for colony survival (Agasyeva *et al*., 2022). Alarm pheromones are deployed in response to perceived threats, eliciting defensive behaviors and rapid dispersal (Amrine Jr *et al*., 2003; Bergmann, 2022). When danger looms, eriophyid mites release these chemical signals to alert nearby conspecifics, triggering coordinated responses that enhance survival (Agasyeva *et al*., 2022). Research on pheromones in mite communication has led to the development of innovative control strategies. For example, synthetic pheromones have been used to disrupt mating behaviors in the apple rust mite (*Aculus schlechtendali*), reducing populations effectively in field trials. These pheromone-based approaches offer a promising avenue for sustainable mite management (Shaw *et al*., 2021).

Semiochemicals

Semiochemicals encompass a broader category of chemical cues utilized by eriophyid mites for interspecific communication, host plant selection, and interactions with natural enemies. They extend beyond pheromones to include a wide array of chemical signals that shape mite behavior: Eriophyid mites are highly attuned to volatile organic compounds (VOCs) emitted by host plants (Childers *et al*., 1996; Zhang *et al*., 2022). These chemical cues guide mites to specific host species or even particular plant organs. They serve as olfactory beacons, directing mites toward suitable feeding and reproduction sites (Takabayashi, 2022). Some eriophyid mites possess the remarkable ability to induce the formation of galls or other structures on host plants through the release of specific chemicals during feeding (Desnitskiy *et al*., 2023; Skoracka *et al*., 2010). These induced changes create protected microenvironments and rich nutrient sources that support mite colonies.

Semiochemicals also mediate interactions between eriophyid mites and their natural enemies. Defensive chemical signals, including alarm pheromones, can deter predators and parasitoids, enhancing mite survival (Choh and Janssen, 2023; Navia *et al*., 2013). These chemical cues contribute to the intricate web of ecological relationships in which eriophyid mites are embedded. The chemical ecology of eriophyid mites is a captivating realm where pheromones, semiochemicals, and host plant volatiles orchestrate intricate communication and behavioral responses. These chemical signals not only ensure the survival and reproductive success of mite populations but also play a broader role in shaping their interactions within agricultural ecosystems.

Interaction with other pests and predators

The interactions between eriophyid mites and other pests and predators are integral components of the complex web of relationships within agricultural ecosystems. These interactions can have profound implications for crop health, pest management, and the overall ecological balance.

Interactions with other pests

Eriophyid mites often share host plants with other arthropod pests, leading to both competitive and facilitative interactions:

Competition for Resources: Eriophyid mites may compete with other pests, such as aphids or spider mites, for access to plant resources (Zhang *et al*., 2023). The overlapping use of host plants can result in resource competition, which may influence population dynamics and damage levels.

Facilitation through Galls: Some eriophyid mite species induce the formation of galls on host plants (Hazra *et al*., 2023). These galls can create protected microenvironments that provide shelter and nutrients not only for eriophyid mites but also for other insects, such as gall-forming aphids or inquilines. These interactions demonstrate how eriophyid mites can indirectly facilitate the presence of other pests through gall formation.

Predation

Eriophyid mites are not immune to predation and parasitism by natural enemies, which can help regulate their populations. Predatory arthropods, such as predatory mites, ladybugs (ladybird beetles), lacewings, and predatory thrips, often feed on eriophyid mites (Yazdanpanah and Fathipour, 2023). These natural enemies can play a crucial role in reducing eriophyid mite populations when their densities are sufficiently high(Song *et al.*, 2023).

Indirect effects on plant health

Eriophyid mites, through their feeding activities and the induction of galls, can indirectly affect plant health. These effects can influence the susceptibility of host plants to other pests and pathogens:

Plant Damage: Eriophyid mites can cause various symptoms on host plants, including leaf curling, bronzing, and gall formation (Rosa-Diaz *et al*., 2023). These symptoms can weaken plants and make them more susceptible to infestations by other pests or infections by plant pathogens.

Disease Transmission: Eriophyid mites can act as vectors for plant pathogens, transmitting viruses or other pathogens during feeding (Song *et al*., 2023). This can further exacerbate the health challenges faced by host plants.

Eriophyid mites engage in intricate interactions with other pests and predators within agricultural ecosystems. These interactions can have cascading effects on crop health, pest management strategies, and the overall ecological balance. Understanding the dynamics of these interactions is essential for developing integrated pest management approaches that account for the broader environmental context.

Molecular Aspects and Genetic Studies

Molecular tools and techniques used in eriophyid mite research

Advancements in molecular biology have revolutionized the study of eriophyid mites, enabling researchers to delve into their genetics, physiology, and molecular interactions with host plants. A wide array of molecular tools and techniques have been employed to unravel the intricacies of these tiny arachnids (Figure 3).

DNA sequencing has played a pivotal role in eriophyid mite research. Techniques such as polymerase chain reaction (PCR) and next-generation sequencing (NGS) allow scientists to amplify and sequence-specific genes or entire genomes. This has led to the identification of mite species, the exploration of genetic diversity within populations, and the discovery of genes involved in various biological processes (Pešić *et al*., 2023). Genetic barcoding consists of the use of specific gene regions, such as the mitochondrial cytochrome c oxidase subunit I (COI) gene, to identify and distinguish eriophyid mite species. This approach provides a rapid and accurate means of species identification, aiding in taxonomic studies and ecological surveys (Yin *et al*., 2022). Transcriptomic studies involve the analysis of gene expression patterns in eriophyid mites. RNA sequencing (RNA-Seq) technology allows researchers to examine the transcriptomes of mites under different conditions or developmental stages. This provides insights into genes involved in feeding, reproduction, and responses to environmental cues (Genath *et al*., 2020).

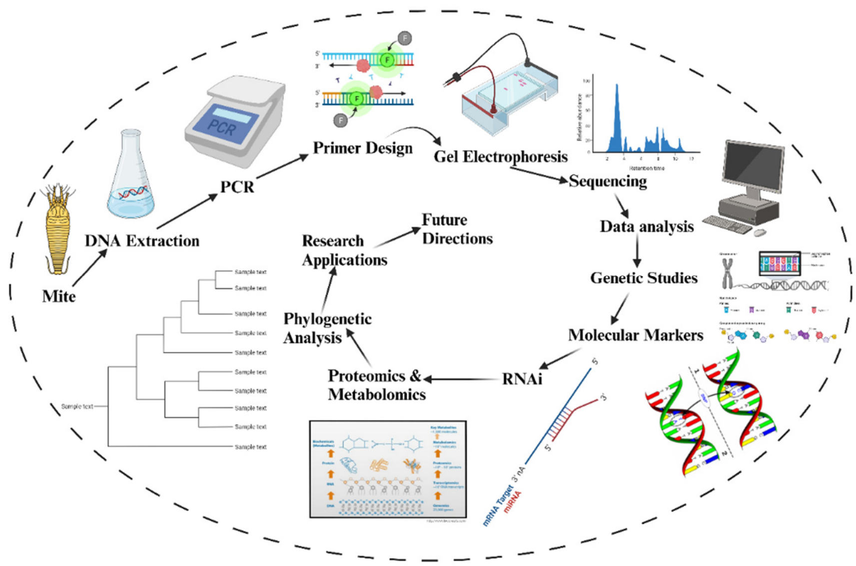

Figure 3. Schematic diagram explaining the molecular tools and techniques commonly used in eriophyid mite research

Proteomic analyses explore the proteins expressed by eriophyid mites. Mass spectrometry and protein profiling techniques enable the identification of proteins involved in crucial biological processes, such as host-plant interactions and the synthesis of enzymes for digestion (Parmagnani et al., 2023). Metagenomics studies focus on the genetic diversity of microbial communities associated with eriophyid mites. This approach uncovers the complex interactions between mites and their microbial symbionts, which can influence mite physiology and ecology (Arribas et al., 2020).

Functional genomics approaches, including RNA interference (RNAi), enable the manipulation of gene expression in eriophyid mites. By silencing specific genes, researchers can investigate their roles in mite biology, behavior, and interactions with host plants (Nganso et al., 2022). Phylogenetic analyses utilize molecular data to reconstruct the evolutionary relationships among eriophyid mite species. These studies help refine taxonomic classifications and provide insights into the evolutionary history of these mites (İnak et al., 2022). The development of genomic resources, including genome databases and molecular markers, has facilitated eriophyid mite research. These resources serve as references for comparative genomics and genetic studies (Bensoussan, 2018; Xiong et al., 2020).

Molecular tools and techniques have significantly advanced our understanding of eriophyid mite biology, genetics, and interactions with host plants. These tools continue to drive research in areas ranging from taxonomy and phylogenetics to functional genomics and metagenomics, shedding light on the complex world of these tiny but ecologically significant arachnids.

Genomic Studies and Insights into Mite Genetics

Genomic studies have revolutionized our understanding of eriophyid mite genetics, providing comprehensive insights into their genomes, genetic diversity, and gene expression patterns. These advancements have deepened our knowledge of the molecular foundations of mite biology and behavior. High-throughput sequencing technologies have enabled the sequencing of complete or partial genomes of various eriophyid mite species. This genomic information has uncovered key genes associated with mite development, reproduction, and responses to environmental stimuli (Zhang et al., 2019). Genome sequencing has provided valuable insights into the genetic architecture of these tiny arachnids.

Comparative genomics has emerged as a powerful approach, allowing researchers to compare genomic data across different mite species. By identifying conserved genes and genetic variations, comparative genomics explores the genetic basis of traits such as host plant specialization and adaptation to diverse environments (Skoracka et al., 2018). It has also facilitated investigations into the evolutionary history and relationships of eriophyid mites within the broader context of arthropod evolution. Transcriptomic studies have illuminated gene expression patterns in eriophyid mites using RNA sequencing (RNA-Seq) technology. These studies reveal how genes are activated or silenced in response to environmental changes or during different life cycle stages (Nganso et al., 2022). They have identified genes crucial for mite feeding, reproduction, and responses to biotic and abiotic factors.

Functional genomics approaches, particularly RNA interference (RNAi), enable the targeted manipulation of gene expression in eriophyid mites (Fang et al., 2022). By selectively silencing specific genes, researchers can delve into their roles in mite biology, behavior, and interactions with host plants. Functional genomics has provided essential insights into the functional significance of mite genes. Genomic studies have also unveiled the genetic diversity within eriophyid mite populations. Through the analysis of genetic markers, researchers have deciphered patterns of genetic variation and population structure. These insights have implications for understanding mite adaptation, dispersal, and responses to environmental changes (Bensoussan, 2018). Genomic studies have advanced our comprehension of eriophyid mite genetics, offering in-depth insights into their genomes, genetic diversity, and gene expression patterns. These findings have far-reaching implications for pest management, as they inform strategies for targeting specific genes or genetic pathways involved in mite biology and host-plant interactions.

Molecular markers for species identification

Molecular markers have become indispensable tools in the identification and differentiation of eriophyid mite species. These markers leverage the unique genetic signatures of mite species, enabling researchers to classify and characterize these tiny arachnids accurately.

One of the most widely employed molecular markers for species identification is mitochondrial DNA (mtDNA) barcoding. The mitochondrial cytochrome c oxidase subunit I (COI) gene has gained prominence as a universal marker for distinguishing eriophyid mite species (Yin *et al.*, 2022). Comparisons of COI gene sequences allow for rapid and precise species identification, even in cases where morphological distinctions are challenging. Microsatellites, also known as simple sequence repeats (SSRs), are another valuable tool for species identification and genetic diversity assessment in eriophyid mites. These short, repetitive DNA sequences exhibit variability among species and populations, making them useful for discriminating between closely related species and elucidating population structures (Bensoussan, 2018; Queiroz *et al*., 2021). Amplicon sequencing, particularly using next-generation sequencing (NGS) platforms, has facilitated the development of multiple genetic markers for species identification. Researchers can target specific regions of the mite genome and amplify them for sequencing. This approach provides a comprehensive view of genetic variation within and between species, aiding in their accurate identification (Edslev *et al*., 2021; Skoracka *et al*., 2018).

Molecular markers also play a crucial role in phylogenetic analyses, which involve the reconstruction of evolutionary relationships among eriophyid mite species. By comparing genetic data, researchers can construct phylogenetic trees that illustrate the evolutionary history and relatedness of different species (Yang *et al*., 2022). These analyses help refine taxonomic classifications and provide insights into the evolutionary dynamics of eriophyid mites. In cases where eriophyid mite species exhibit cryptic diversity or form species complexes with subtle morphological differences, molecular markers have been instrumental in resolving taxonomic uncertainties. Genetic markers reveal hidden diversity and assist in delineating species boundaries within these complexes (Navajas *et al*., 2010).

The use of molecular markers for species identification not only enhances the accuracy of eriophyid mite taxonomy but also aids in ecological and epidemiological studies. It allows researchers to trace the geographic distribution and movement of specific mite species, providing valuable information for pest management and conservation efforts.

Host-plant interactions at the molecular level

Understanding the intricate interactions between eriophyid mites and their host plants at the molecular level is central to unravelling the mechanisms that govern mite feeding, reproduction, and adaptation to specific plant species. Molecular studies have shed light on these complex relationships.

At the heart of host-plant interactions lies the battle between mites and the host's defense mechanisms. Molecular investigations have elucidated the strategies employed by both mites and plants in this arms race. Mites often secrete effector molecules that manipulate plant responses, allowing them to feed and reproduce (Chen *et al*., 2023). These effectors have been identified and characterized at the molecular level, revealing their role in overcoming plant defenses. Plant responses to eriophyid mite infestation involve the activation of various molecular pathways. Transcriptomic studies have uncovered the genes and signaling pathways that are upregulated in response to mite feeding. This includes the expression of defense-related genes and the production of secondary metabolites that can deter mite herbivory (Zhang *et al*., 2023). Understanding these molecular responses is vital for developing strategies to enhance plant resistance to mite infestation. Eriophyid mite species often exhibit host specialization, infesting specific plant species or genera. Molecular studies have revealed genetic adaptations in mite populations that allow them to exploit particular host plants (Skoracka *et al*., 2018). These adaptations may involve changes in detoxification mechanisms to overcome plant toxins or the evolution of effector molecules tailored to their host.

Molecular research has also unveiled the intricate signaling processes that occur between plants and eriophyid mites. Chemical cues and signaling molecules play a crucial role in mediating these interactions. Identifying the specific molecules involved in plant-mite signaling provides insights into the communication between the two organisms (Yin *et al*., 2022). Molecular insights into host-plant interactions have practical applications in pest management and crop breeding. Understanding how mites interact with their host plants at the molecular level can inform the development of biological control strategies and the breeding of resistant crop varieties (Bensoussan, 2018). These strategies aim to disrupt the molecular mechanisms that facilitate mite infestation. Molecular studies have deepened our understanding of host-plant interactions in eriophyid mites, unveiling the molecular mechanisms behind mite feeding, plant responses, and mite adaptation to host plants. These insights have practical implications for pest management and crop protection, offering potential avenues for enhancing plant resistance and reducing mite damage.

Control Strategies

This section reviews various control strategies for eriophyid mites, including chemical, biological, cultural, and integrated pest management (IPM) approaches. Each subsection will discuss the methods, efficacy, and conditions for optimal use, providing a comprehensive overview of current and emerging control strategies (Figure 4).

Chemical control methods

<u>Acaricides and their efficacy</u>

Chemical control, through the use of acaricides, has long been a primary strategy for managing eriophyid mite infestations in agricultural settings. Acaricides are chemical agents designed to target and eliminate mite populations (Table 4). The efficacy of these chemicals depends on various factors, including the specific acaricide used, mite species, and application methods (Sreekumar *et al*., 2019). Several classes of acaricides are employed to combat eriophyid mites, including organophosphates, pyrethroids, and neonicotinoids, among others (Palmer and Vea, 2012; Selvaraj *et al*., 2018; Suganthi *et al*., 2006). The choice of acaricide depends on factors such as local regulations, mite species, and the stage of mite infestation. Organophosphates, for instance, have been widely used, but their effectiveness can be reduced due to mite resistance (Marcic, 2012).

The efficacy of acaricides can vary based on mite susceptibility and life stage. Eriophyid mite eggs and immatures, for example, maybe more vulnerable to certain acaricides than adults. Factors such as application timing, dosage, and frequency also influence acaricide effectiveness (El-Banhawy and El-Bagoury, 1985). Integrated Pest Management (IPM) strategies often involve monitoring mite populations to determine the optimal timing for acaricide applications (Kolcu and Kumral, 2023; Revynthi *et al*., 2022). A major challenge in chemical control is the development of mite resistance to acaricides. Eriophyid mite populations can evolve resistance mechanisms, rendering certain chemicals ineffective (Roseleen and Ramaraju, 2012; Vinaykumar *et al*., 2022). This highlights the importance of rotating or combining different classes of acaricides to delay resistance development.

<u>Resistance mechanisms</u>

Mites may possess enzymes that metabolize or detoxify acaricides, rendering them less harmful. These detoxification enzymes, such as cytochrome P450 monooxygenases, can break down acaricides into less toxic compounds, allowing mites to survive exposure (Bachhar *et al*., 2019; Sharma *et al*., 2019). Resistance can also result from mutations in the molecular target sites of acaricides. These mutations reduce the binding affinity of acaricides to their target sites, diminishing their lethal effects on mites (Van Leeuwen *et al.*, 2009). Mites may exhibit behavioral adaptations that reduce exposure to acaricides. These adaptations may include avoiding treated areas, seeking shelter, or altering feeding patterns (Adesanya *et al*., 2021).

To address the issue of acaricide resistance, integrated pest management (IPM) approaches have gained prominence. IPM combines various control methods, including chemical, biological, and cultural strategies, to minimize the reliance on acaricides and delay resistance development. Monitoring mite populations, using selective acaricides, and promoting natural predators of eriophyid mites are key components of IPM programs. Chemical control methods, particularly the use of acaricides, play a significant role in managing eriophyid mite infestations. However, their effectiveness is influenced by factors such as mite species and resistance mechanisms. Understanding resistance mechanisms is vital for developing sustainable pest management strategies and integrating chemical control into broader IPM programs.

Table 4. Comparative efficacy of chemical acaricides for eriophyid mite control

Acaricide	Active ingredient	Mode of action	Resistance status	References
Abamectin	Abamectin	Neurotoxin; disrupts nervous system	Low resistance reported; limited cases	(El-Banhawy and El-Bagoury, 1985; Revynthi *et al.*, 2022; Roseleen and Ramaraju, 2012)
Bifenazate	Bifenazate	Mitochondrial complex III inhibitor	Low resistance reported; limited cases	(Kolcu and Kumral, 2023; Van Leeuwen *et al*., 2010)
Spiromesifen	Spiromesifen	Lipid biosynthesis inhibitor	Low resistance reported; limited cases	(Selvaraj *et al.*, 2018; Suganthi *et al*., 2006; Vinaykumar *et al.*, 2022)

Fenpyroximate	Fenpyroximate	Mitochondrial complex I inhibitor	Low resistance reported; limited cases	(Palmer and Vea, 2012; Sreekumar *et al*., 2019; Vinaykumar *et al*., 2022)
Hexythiazox	Hexythiazox	Chitin synthesis inhibitor	Low resistance reported; limited cases	(Arreguin-Zavala *et al*., 2021; Palmer and Vea, 2012)
Clofentezine	Clofentezine	Mitochondrial complex II inhibitor	Low resistance reported; limited cases	(Bhuvaneswari *et al*., 2022; Schmidt-Jeffris *et al*., 2019)
Tebufenpyrad	Tebufenpyrad	Mitochondrial complex I inhibitor	Low resistance reported; limited cases	(Bhuvaneswari *et al*., 2022; Kolcu, 2019; Kolcu and Kumral, 2023)
Pyridaben	Pyridaben	Mitochondrial complex I inhibitor	Low resistance reported; limited cases	(Kolcu and Kumral, 2023; Kumral *et al*., 2021)
Spirodiclofen	Spirodiclofen	Lipid biosynthesis inhibitor	Low resistance reported; limited cases	(Abo-Shnaf *et al*., 2022; Perkins *et al*., 2021)
Fenbutatin oxide	Fenbutatin oxide	Mitochondrial complex II inhibitor	Low resistance reported; limited cases	(County; Kolcu & Kumral, 2023; Kumral *et al*., 2021)

Biological control agents

Biological control represents an eco-friendly and sustainable approach to managing eriophyid mite infestations in agriculture. This strategy harnesses natural enemies and beneficial organisms to regulate mite populations, thereby reducing their impact on crops (Joshi *et al*., 2023). Several biological control agents have been explored and implemented to combat eriophyid mites effectively.

Predatory mites

Predatory mites belonging to families, such as Phytoseiidae, are prominent natural enemies of eriophyid mites. These beneficial mites are voracious predators that feed on eriophyid mite eggs, immatures, and adults (Demard *et al*., 2023; Hajizadeh and Hosseini, 2023b). Prominent species like *Phytoseiulus persimilis* and *Neoseiulus californicus* have been extensively used in biological control programs (Möth *et al*., 2023; Sarwar, 2019). Their effectiveness in eradicating mite populations hinges on factors such as temperature, humidity, and the availability of prey. These are most effective under specific ecological conditions such as moderate temperatures (20-30 °C) and high humidity levels (60-80%). These predatory mites thrive in environments with abundant prey and can be integrated into pest management programs where such conditions are met, enhancing their efficacy in controlling eriophyid mite populations (Kaur and Bhullar, 2015; Van Leeuwen *et al*., 2010).

Lady Beetles (Ladybugs)

Lady beetles, particularly species like *Stethorus* spp., are known predators of eriophyid mites. They feed on mite eggs and nymphs, helping to reduce mite populations (Kalile *et al*., 2023; Serber, 2022). Encouraging the presence of lady beetles in agricultural ecosystems can be achieved through habitat management and the avoidance of broad-spectrum insecticides that may harm these beneficial insects (Mohan *et al*., 2022).

Entomopathogenic nematodes

Certain species of entomopathogenic nematodes, such as *Steinernema feltiae*, exhibit potential for controlling eriophyid mites. These nematodes infect and kill mite stages present in the soil or leaf litter, providing a biological alternative for mite management (Shahid *et al*., 2023; Sharma *et al*., 2023). Their efficacy depends on factors like soil moisture and temperature (Chaubey and Aasha, 2021).

Predatory insects

Predatory insects, including lacewings (Chrysopidae) and minute pirate bugs (Anthocoridae), can serve as natural enemies of eriophyid mites (Sathish *et al*., 2019). These insects are generalist predators that consume various small arthropods, including mites (Abdel-Khalek and Momen, 2022). Incorporating diverse vegetation and avoiding excessive pesticide use can create favorable conditions for these predators.

Fungal pathogens

Entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, have demonstrated potential for eriophyid mite control (Sathish *et al*., 2019). These fungi infect and kill mites upon contact (Prajapati *et al*., 2022). Application methods and environmental conditions influence the efficacy of fungal pathogens in the field (Minguely *et al*., 2021).

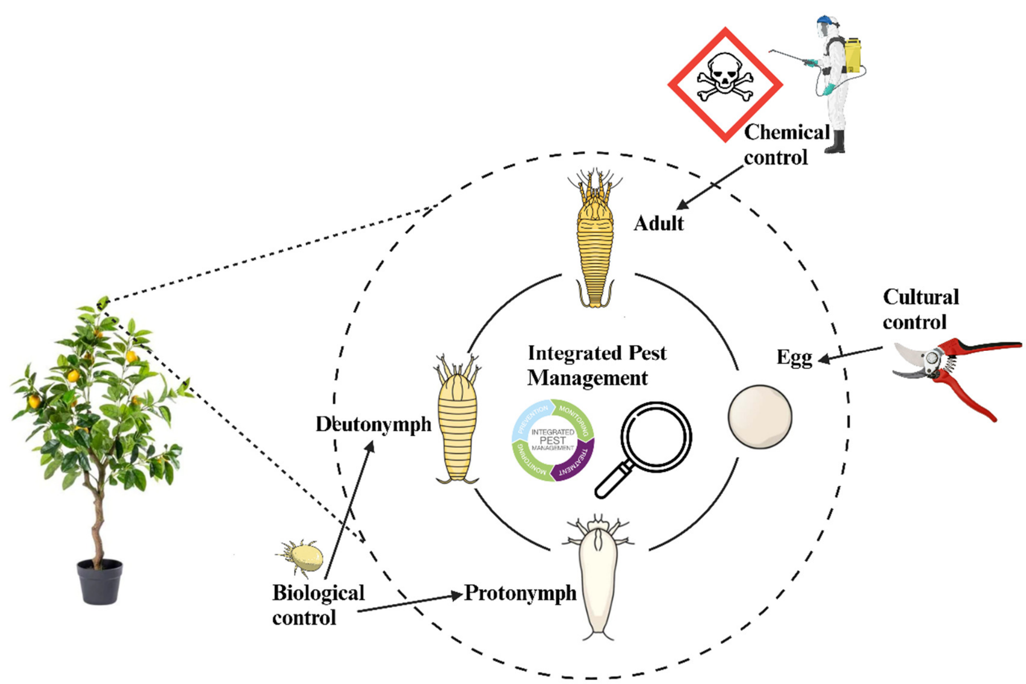

Figure 4. Life cycle of eriophyid mites alongside key control points where different strategies (chemical, biological, cultural) can be implemented

Advantages of biological control

Biological control offers several advantages, including reduced chemical pesticide use, minimal environmental impact, and long-term sustainability. It can be integrated into existing pest management programs and is particularly beneficial for organic farming systems. Moreover, biological control agents exhibit no risks of resistance development compared to chemical acaricides (Minguely *et al*., 2021).

Challenges and considerations

Effective biological control of eriophyid mites requires a thorough understanding of the biology and ecology of both the pest mite and its natural enemies. Factors such as timing, release rates, and habitat management are critical for success. Additionally, the compatibility of biological control agents with other pest management practices should be considered in integrated pest management (IPM) programs.

Biological control agents offer a sustainable and environmentally friendly approach to managing eriophyid mite infestations in agriculture. Predatory mites, lady beetles, entomopathogenic nematodes, predatory insects, and fungal pathogens are valuable allies in the battle against these crop-damaging pests. Integrating biological control into pest management practices can reduce reliance on chemical acaricides and contribute to the long-term health of agricultural ecosystems.

Cultural and physical control methods

In addition to chemical and biological control strategies, cultural and physical control methods play a crucial role in managing eriophyid mite infestations, offering sustainable and environmentally friendly alternatives for growers.

Crop rotation is a fundamental cultural control practice that helps break the life cycle of eriophyid mites. By planting non-host crops in rotation with susceptible ones, mite populations are deprived of their primary food source. This interrupts the buildup of mite populations and reduces the need for chemical intervention (Dively *et al*., 2022). Good agricultural practices include removing and destroying infested plant material, especially during the dormant season. This reduces overwintering sites and disrupts the mites' life cycle. Regular pruning and removal of plant debris can help prevent mite infestations in subsequent seasons (Brown *et al*., 2021). Weeds can serve as alternative hosts for eriophyid mites. Implementing effective weed management strategies can help reduce the reservoir of mites in and around the crop field. Herbicide application, mulching, or cultivation practices can be employed to control weeds (Van Leeuwen *et al.*, 2010).

Mechanical leaf removal involves the physical removal of infested leaves or plant parts. This can be done using equipment like leaf blowers or vacuum devices. Removing infested plant material helps reduce mite populations and limits the spread of the infestation to healthy plant parts (Brown *et al*., 2021). High-pressure water sprays can be used to dislodge and wash away eriophyid mites from plant surfaces. This method is particularly effective for controlling mites in ornamental plants and certain crops. It is a non-chemical and environmentally friendly approach (Chong, 2022). Modifying the crop environment through practices like adjusting planting density, reducing plant stress, and optimizing irrigation can affect the microclimate and impact mite populations. Eriophyid mites are sensitive to environmental conditions, and creating an unfavorable habitat can hinder their development and reproduction (Chong, 2022). Physical barriers, such as fine mesh netting or row covers, can be employed to prevent mite infestations. These barriers block mites from reaching the plants, providing a protective shield against infestations (Chong, 2022).

The integration of cultural and physical control methods into an overall pest management strategy, along with chemical and biological control approaches, enhances the effectiveness of eriophyid mite management. These methods are especially valuable in organic farming systems and are key components of integrated pest management (IPM) programs. Implementing a combination of control strategies tailored to the specific crop and mite species can help reduce reliance on chemical acaricides and minimize the environmental impact of mite management practices.

Integrated Pest Management (IPM) strategies

Integrated Pest Management (IPM) is a holistic and sustainable approach to managing eriophyid mite infestations while minimizing the reliance on chemical acaricides. IPM strategies incorporate various control methods, including chemical, biological, cultural, and physical approaches, to maintain mite populations at levels that do not cause significant crop damage.

The foundation of any successful IPM program is regular monitoring and scouting for eriophyid mite populations. This involves assessing mite presence, density, and distribution within the crop. Monitoring allows growers to make informed decisions about the timing and choice of control measures. Tools like sticky traps, leaf examination, and sampling techniques are commonly used to assess mite populations (Brown *et al*., 2021). IPM programs establish action thresholds based on mite population levels and economic damage potential. These thresholds guide decisions about when control measures are necessary. By setting thresholds, growers can avoid unnecessary chemical applications and reduce the risk of resistance development (Chong, 2022). Cultural practices, such as crop rotation, sanitation, and weed management, are integral components of IPM. Crop rotation disrupts the mite life cycle by planting non-host crops in rotation with susceptible ones. Sanitation involves the removal and destruction of infested plant material, reducing overwintering sites for mites. Effective weed management decreases alternative hosts for eriophyid mites (Brown *et al*., 2021).

IPM programs promote the use of biological control agents, such as predatory mites, lady beetles, and entomopathogenic nematodes, to regulate mite populations. These natural enemies help maintain mite populations below damaging levels. Incorporating habitat management practices that support the presence of beneficial insects is crucial for successful biological control (Incedayi *et al*., 2021). While chemical control is a component of IPM, it is used judiciously and as a last resort. When mite populations exceed action thresholds and other control measures are insufficient, selective acaricides are employed. IPM emphasizes the use of less toxic chemicals, rotation of acaricide classes, and adherence to recommended application rates and timings to minimize the risk of resistance (Dively *et al*., 2022). IPM programs emphasize the importance of record-keeping in tracking mite populations, the control measures applied, and their effectiveness. Evaluation of the program's success is ongoing, allowing for adjustments in control strategies based on real-time data. This adaptive approach ensures that control measures remain effective over time (Vervaet *et al*., 2021). Education and training are essential aspects of IPM implementation. Growers, agricultural advisors, and pest control professionals need to be informed about eriophyid mite biology, monitoring techniques, and the principles of IPM. Training programs ensure that stakeholders can make informed decisions and implement IPM strategies effectively (Chandrashekar *et al*., 2020). A successful IPM approach was implemented in the citrus orchards of Southern California, where a combination of cultural practices, biological controls, and selective acaricide applications were used. This case study highlights the integration of crop rotation, sanitation measures, and the introduction of *Phytoseiulus persimilis*, resulting in a significant reduction in mite populations and improved crop yields over three growing seasons (Rodrigues *et al.*, 2011).

<u>Novel and emerging control approaches</u>

In the ongoing quest for sustainable and effective control of eriophyid mites, researchers and agricultural practitioners are exploring novel and emerging approaches that offer promise for managing these tiny but troublesome pests (Figure 5). These innovative strategies go beyond traditional control methods and leverage advancements in technology, genetics, and ecological understanding.

<u>RNA Interference (RNAi) technology</u>

RNA interference (RNAi) has emerged as a powerful tool for pest management in various agricultural systems. In the context of eriophyid mites, RNAi technology offers the potential to silence specific genes in mites responsible for essential biological functions. By targeting genes critical to mite survival or reproduction, RNAi can disrupt mite populations without harming beneficial organisms or non-target species (Sarwar, 2020). While RNA interference (RNAi) shows promise for eriophyid mite control, its widespread adoption is hindered by challenges such as efficient delivery methods, potential off-target effects, and the high costs associated with RNAi technology. Further research is needed to overcome these barriers and make RNAi a viable option for large-scale agricultural use (Zhu and Palli, 2020).

Use of natural predators

Exploring and promoting native or introduced natural predators and parasitoids specific to eriophyid mites can be an effective strategy. Identifying and enhancing the populations of these natural enemies can help maintain eriophyid mite populations at manageable levels. Research into the natural enemies of eriophyid mites, such as predatory beetles, and other arthropods, is ongoing (Shukla, 2021).

Genetically engineered host plants

Genetic modification of host plants to confer resistance to eriophyid mites is an emerging approach. Scientists are investigating the potential for developing genetically engineered crops that produce compounds or proteins harmful to mites upon feeding. These plants could reduce mite damage and minimize the need for chemical control measures (Zhang *et al*., 2023).

Semiochemical-based control

Semiochemicals, including pheromones and kairomones, play a vital role in mite behavior and communication. Research into the use of semiochemicals for monitoring and control is expanding. Pheromone-based traps and attract-and-kill strategies are being developed to disrupt mite mating and foraging patterns, ultimately reducing populations (Kennedy and Lekshmi, 2022).

Nanotechnology and microbial control

Nanotechnology applications, such as the development of nanoencapsulated acaricides, hold the potential for targeted and controlled release of pesticides to eriophyid mites. Additionally, microbial control agents, such as entomopathogenic fungi, are being explored for their effectiveness against mite populations while minimizing environmental impact (Al-Azzazy and Ghani, 2023).

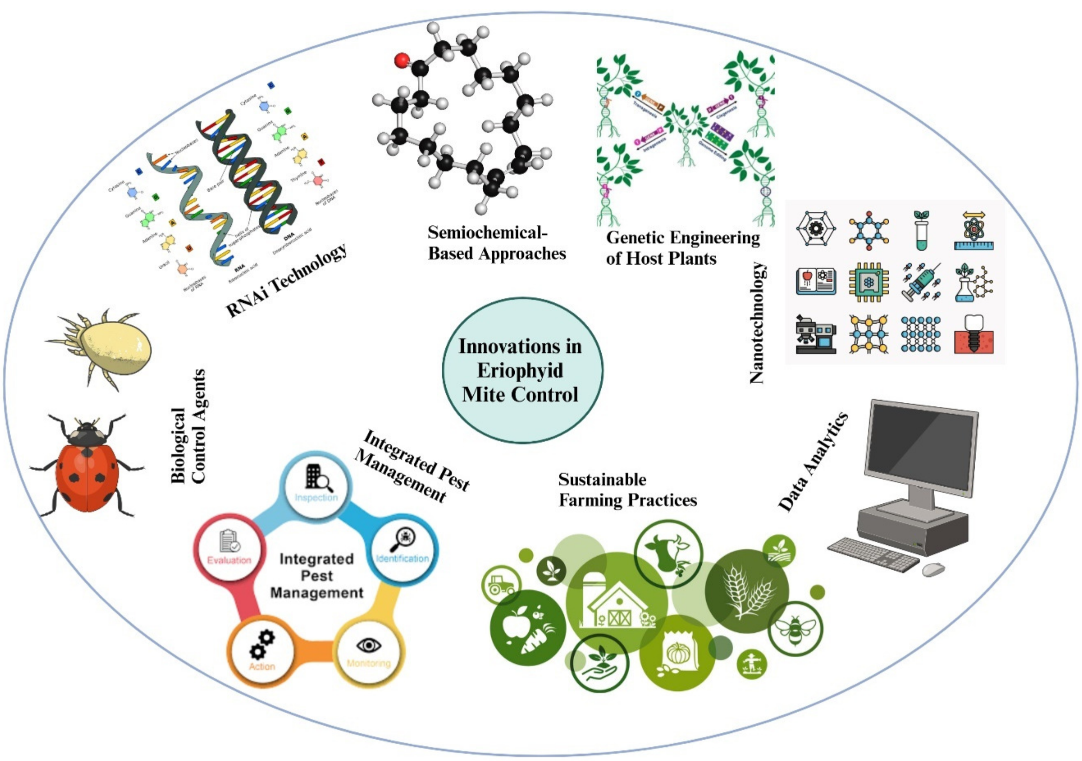

Figure 5. Potential innovations in eriophyid mite control

Remote sensing and precision agriculture

Advancements in remote sensing and precision agriculture technologies are enabling growers to detect eriophyid mite infestations at an early stage. Drones, satellites, and other remote sensing tools can monitor crop health and identify areas of potential mite damage. This allows for targeted interventions, reducing the overall need for chemical control (Dively *et al*., 2022).

Climate-resilient cultivars

As climate change affects the distribution and behavior of eriophyid mites, the development of climate-resilient crop cultivars becomes crucial. Breeding programs focus on selecting and developing crop varieties that can withstand mite infestations and associated environmental stresses (Dively *et al*., 2022).

The pursuit of novel and emerging control approaches for eriophyid mites reflects the ongoing commitment to sustainable and environmentally friendly pest management. These innovative strategies, driven by advancements in science and technology, offer potential solutions to the challenges posed by eriophyid mites while reducing the ecological footprint of mite control in agriculture.

Research Gaps and Unanswered Questions

In the realm of eriophyid mite management, numerous research gaps and unresolved questions persist, demanding further exploration and scientific inquiry. These knowledge deficits are pivotal in shaping effective control strategies and deepening our comprehension of these minute but influential pests.

One key avenue of inquiry revolves around the biology of eriophyid mites, particularly the molecular intricacies of their feeding behaviors. A comprehensive grasp of the molecular mechanisms governing eriophyid mite feeding and their interactions with host plants is an uncharted territory ripe for exploration. Delving into the genomic and transcriptomic landscape of these mites holds the potential to illuminate their biology, physiology, and adaptive capabilities, thus offering a foundation for the development of innovative control approaches such as RNA interference (RNAi). Host-plant interactions represent another enigmatic facet. An essential query centers on the factors that precipitate the expansion of eriophyid mites' host ranges. Unraveling the genetic determinants and ecological drivers underpinning host-switching events is imperative. Moreover, investigations into the defense mechanisms triggered in plants during eriophyid mite infestations hold promise for enhancing crop resistance.

Chemical ecology is a field brimming with potential, awaiting meticulous exploration. Identifying and characterizing the pheromones and semiochemicals governing eriophyid mite communication and behavior demands focused investigation. Discerning the chemical constituents and ecological significance of these compounds is a critical precursor to their application in monitoring and control strategies, offering prospects for novel approaches such as attract-and-kill methodologies. Future research should focus on identifying specific pheromones and semiochemicals involved in eriophyid mite behavior. Key questions include: How do these chemical signals vary among different species? Can we develop synthetic analogs for use in pest management? What are the environmental impacts of deploying these semiochemicals at scale?

Resolving the conundrum of acaricide resistance in eriophyid mites represents a pressing challenge. Probing the mechanisms underpinning resistance, including the genetic underpinnings and modes of resistance propagation within populations, is pivotal. This knowledge serves as the foundation for devising strategies to counter resistance effectively. Research into alternative control methods is an evolving frontier. The evaluation of entomopathogenic fungi, microbial agents, and natural enemies as potential eriophyid mite management tools is paramount. Rigorous assessments of their efficacy under diverse environmental conditions are essential, allowing for informed integration into pest management programs.

The shadow of climate change looms large over eriophyid mite behavior. Investigating the repercussions of climate change on mite distribution, phenology, and life cycles is essential. This research aids in anticipating range shifts and phenological alterations, furnishing growers with vital insights for adaptive management. Enhancing molecular tools for species identification, particularly in scenarios where morphological identification presents challenges, remains a research priority. The expansion of species-specific molecular markers holds the key to accurate and efficient identification. Quantifying the economic losses inflicted by eriophyid mite infestations on diverse crops and regions is pivotal for directing research and management endeavors. Simultaneously, probing the ecological ramifications of these infestations on non-target species, ecosystem dynamics, and biodiversity forms an integral aspect of comprehending their broader environmental impact.

Addressing these research gaps and unanswered questions is instrumental in forging sustainable and efficacious strategies for eriophyid mite management. Collaborative efforts among researchers, growers, and policymakers are indispensable for prioritizing research endeavors and translating findings into pragmatic agricultural solutions.

Conclusions

The knowledge gaps and research priorities identified in this review underscore the need for sustained efforts in mite research. Priority research areas include the molecular mechanisms governing eriophyid mite feeding and host-plant interactions, the development of climate-resilient cultivars, and the enhancement of molecular tools for species identification. Emerging technologies close to practical implementation include RNA interference (RNAi) technology and semiochemical-based approaches. However, practical challenges remain in implementing these strategies in conventional farming systems, such as the high cost of RNAi technology and the environmental impacts of deploying semiochemicals at scale. Overcoming these challenges requires collaborative efforts among researchers, growers, and policymakers. Additionally, a comparative analysis of the effectiveness of different mite control strategies, including chemical, biological, cultural, and IPM approaches, highlights the need for integrated pest management practices to achieve sustainable control of eriophyid mites in fruit crop systems.

Authors' Contributions

Conceptualization, S.U.M. and X.F.; writing—original draft preparation, S.U.M. and I.U.H.; writing—review and editing, S.U.M., X.F., R.M. and I.U.H.; project administration, X.F. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

Funding

This work was supported by the GDAS Special Project of Science and Technology Development (2022GDASZH-2022010106).

Acknowledgements

We would like to express our gratitude to the Guangdong Key Laboratory of Animal Conservation and Resource Utilization and the Institute of Zoology, Guangdong Academy of Sciences, for their invaluable support and resources.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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