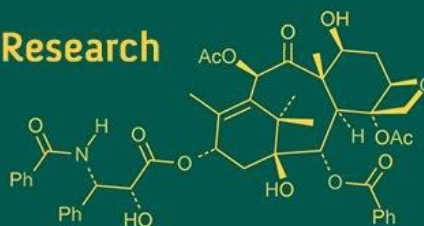


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Integrated pest and disease management in sericulture: Emerging approaches and sustainable solutions

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Abstract

Sericulture, the cultivation of silkworms for silk production, is a vital agro-industry providing livelihoods for millions globally. However, its sustainability is perpetually threatened by a complex of insect pests and diseases affecting both the mulberry host plant (*Morus* spp.) and the silkworm, *Bombyx mori*. The over-reliance on chemical pesticides has led to environmental contamination, harm to non-target organisms and the development of resistance, compromising the quality of mulberry leaves and silkworm health. This review critically synthesizes current research on Integrated Pest and Disease Management (IPDM) in sericulture, emphasizing the shift towards sustainable and eco-friendly solutions. We examine the biology and impact of major pests, including the tukra mealybug (*Maconellicoccus hirsutus*) and leaf roller (*Diaphania pulverulentalis*) and devastating silkworm diseases such as muscardine (caused by *Beauveria bassiana*) and pebrine (caused by *Nosema bombycis*). The core of the review focuses on emerging management strategies, integrating biological control using parasitoids and entomopathogens, botanical pesticides derived from plants like neem (*Azadirachta indica*) and advanced cultural practices. Furthermore, we explore the transformative potential of biotechnology, including molecular diagnostics for rapid pathogen detection, RNA interference (RNAi) for targeted pest suppression and the development of pest-resistant mulberry cultivars. The integration of digital technologies like AI-based pest detection and IoT-enabled environmental monitoring is also discussed as a frontier in precision sericulture. Key challenges, such as climate change impacts and barriers to farmer adoption, are addressed. Future research should focus on microbiome engineering for disease resilience, validating biocontrol agents under field conditions and developing climate-smart sericulture models to ensure the long-term economic and ecological sustainability of the silk industry.

Keywords: *Bombyx mori*, sericulture, integrated pest management, silkworm diseases, biological control, sustainable agriculture, mulberry pests and RNA interference

1. Introduction

Sericulture, the ancient practice of rearing silkworms (*Bombyx mori* L.) for the production of raw silk, represents a unique intersection of agriculture and textile industry with a history spanning over 5,000 years (Cappellozza *et al.*, 2022)^[1]. Originating in China, this agro-based enterprise has evolved into a significant global industry, providing employment and economic stability to millions of rural families, particularly in developing nations like China and India, the world's leading silk producers (Sharma and Kapoor, 2020)^[2]. The domestic silkworm, *B. mori*, is a lepidopteran insect that is entirely dependent on the leaves of the mulberry plant (*Morus* spp.) for its nutrition. Consequently, the success of sericulture is intrinsically linked to the health and productivity of both the silkworm and its sole food source. The quality and quantity of mulberry foliage directly influence larval growth, cocoon characteristics and ultimately, the yield and quality of silk filament (Islam *et al.*, 2022a)^[3]. Despite its economic importance, the sericulture industry faces persistent and formidable challenges from a wide array of pests and diseases. Mulberry plantations are attacked by over 300 species of insect and non-insect pests, which can be broadly categorized as defoliators, sap-suckers and borers (Narayanaswamy *et al.*, 1996)^[4]. Pests such as the pink mealybug (*Maconellicoccus hirsutus*), thrips (*Pseudodendrothrips mori*) and leaf roller (*Diaphania pulverulentalis*) cause significant quantitative and qualitative losses in leaf yield, ranging

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from 10% to over 30% (Manjunath *et al.*, 2003; Islam *et al.*, 2025) ^[5, 6]. These infestations not only reduce the available biomass for silkworm rearing but also diminish the nutritional content of the leaves by hampering photosynthesis, which in turn adversely affects silkworm growth and cocoon production (Bhagyamma and Kumari, 2022) ^[7].

Simultaneously, the silkworm itself is highly susceptible to a variety of pathogenic diseases, which are a primary cause of crop failure and economic loss in sericulture. These diseases are caused by viral (Grasserie), bacterial (Flacherie), fungal (Muscardine) and protozoan (Pebrine) agents. Pebrine, caused by the microsporidian *Nosema bombycis*, is particularly devastating as it can be transmitted transovarially, leading to systemic infection and high mortality (Hu *et al.*, 2021) ^[8]. White muscardine, caused by the entomopathogenic fungus *Beauveria bassiana*, is another major threat, especially during cooler, humid seasons, causing larvae to become mummified and resulting in substantial crop losses (Lu *et al.*, 2021) ^[9]. These diseases collectively account for significant annual losses, estimated in the millions of dollars in major silk-producing countries (Pan *et al.*, 2017) ^[10].

Historically, the primary response to these pest and disease pressures has been the application of broad-spectrum chemical pesticides and disinfectants. While offering a temporary reduction in pest populations, this strategy has proven to be unsustainable. The indiscriminate use of chemical agents in mulberry fields leads to several detrimental consequences: (1) toxic residues on mulberry leaves, which are harmful or lethal to the highly sensitive silkworms; (2) destruction of beneficial, non-target organisms, including natural enemies of pests, thereby disrupting ecological balance; (3) contamination of soil, water and air, posing risks to environmental and human health (Pimentel *et al.*, 1992) ^[11]; and (4) the rapid development of pesticide resistance in target pest populations (Singh *et al.*, 2025) ^[12]. The limited number of chemicals approved for use in mulberry, such as dichlorvos, further constrains chemical control options (David and Ramamurthy, 2011) ^[13].

These limitations have necessitated a paradigm shift towards a more holistic and sustainable approach: Integrated Pest and Disease Management (IPDM). IPDM is an ecosystem-based strategy that focuses on long-term prevention of pests and diseases through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices and use of resistant varieties (Stenberg, 2017) ^[14]. Chemical controls are used only as a last resort and with a focus on selectivity and minimal environmental impact. The goal of IPDM is not pest eradication but to maintain pest and pathogen populations below economic threshold levels (ETLs), ensuring both economic viability and ecological sustainability (Barzman *et al.*, 2015) ^[15].

This review aims to provide a comprehensive overview of the current status and future directions of IPDM in sericulture. We will critically examine the major pests and diseases threatening the industry and synthesize the latest research on sustainable management strategies. This includes an in-depth analysis of biological control agents, botanical pesticides, cultural and preventive measures and cutting-edge molecular and digital technologies. By integrating these diverse approaches, this review seeks to outline a robust framework for a resilient, productive and

environmentally responsible sericulture industry for the 21st century.

2. Major Mulberry Pests in Sericulture

The health and nutritional quality of mulberry leaves are paramount for successful silkworm rearing. A diverse complex of insect pests infests mulberry plantations, causing significant damage that reduces both leaf yield and quality, thereby directly impacting cocoon production. These pests can be broadly classified based on their feeding habits into sap-suckers and defoliators.

2.1 Tukra Mealybug (*Maconellicoccus hirsutus*)

The pink hibiscus mealybug, *Maconellicoccus hirsutus* (Hemiptera: Pseudococcidae), is one of the most destructive pests of mulberry in tropical and subtropical regions (Mani, 1989) ^[16]. This polyphagous sap-sucking insect infests the apical shoots of mulberry plants. During feeding, it injects toxic saliva into the plant tissues, leading to a characteristic symptom known as “tukra.” Tukra is characterized by stunting of apical growth, crinkling and curling of leaves and a swollen, deep green appearance of the affected shoots (Manjunath *et al.*, 2003) ^[5]. The infested leaves become unsuitable for silkworm feeding and severe infestations can lead to an estimated leaf yield loss of up to 4,500 kg/ha/year (Manjunath *et al.*, 2003) ^[5]. The pest’s waxy coating protects it from adverse environmental conditions and contact insecticides, making it difficult to control. Studies have shown that abiotic factors, particularly temperature and humidity, significantly influence its population dynamics (Rahmathulla *et al.*, 2015) ^[17].

2.2 Thrips (*Pseudodendrothrips mori*)

Mulberry thrips, *Pseudodendrothrips mori* (Thysanoptera: Thripidae), are minute, slender insects that feed by piercing and sucking cell contents from the leaf surface, primarily on the ventral side. This feeding activity results in the appearance of silvery-white streaks and patches on the leaves. Heavily infested leaves become coarse, brittle and lose their nutritional value (Mahadeva, 2011) ^[18]. The damage hampers photosynthesis and reduces key biochemical constituents like proteins and carbohydrates, which are essential for silkworm growth (Mahadeva and Nagaveni, 2011) ^[19]. Leaf yield loss due to thrips infestation has been reported to be around 22% (Lalitha *et al.*, 2018) ^[20]. Their small size and cryptic habits make monitoring and control challenging. Population build-up is often favored by warm and dry weather conditions.

2.3 Spiralling Whitefly (*Aleurodicus dispersus*)

The spiralling whitefly, *Aleurodicus dispersus* (Hemiptera: Aleyrodidae), is an invasive polyphagous pest that has become a significant threat to mulberry cultivation. Both nymphs and adults suck sap from the underside of leaves, causing yellowing, curling and premature leaf drop. A key characteristic of this pest is the copious amount of honeydew it excretes, which promotes the growth of sooty mold on leaf surfaces (Waterhouse and Norris, 1989) ^[21]. This black fungal growth interferes with photosynthesis and respiration, drastically reducing the quality of the foliage. Silkworms refuse to feed on leaves coated with sooty mold. Severe infestations can reduce leaf yield by over 28% (Rashid *et al.*, 2003) ^[22]. The pest completes its life cycle rapidly, leading to overlapping generations and rapid population build-up.

2.4 Leaf Roller/Webber (*Diaphania pulverulentalis*)

The mulberry leaf roller, *Diaphania pulverulentalis* (Lepidoptera: Pyralidae), is a major defoliating pest, particularly in South and East Asia. The early instar larvae feed on tender apical leaves, while later instars roll or web together several leaves to form a protective shelter within which they feed (Geetha Bai *et al.*, 1997) ^[23]. This feeding behavior not only destroys the leaves but also contaminates the remaining foliage with fecal matter, rendering it unfit for silkworm consumption. Infestations are most severe during the post-monsoon season, with population build-up correlating with decreasing temperatures and increasing humidity (Kumar *et al.*, 2021) ^[24]. Leaf yield loss due to this pest can reach up to 15% (Manjunath *et al.*, 2005) ^[25]. Furthermore, the pest has been identified as a potential carrier of pathogens like *Nosema bombycis*, posing a secondary threat to silkworm rearing (Ifat *et al.*, 2011) ^[26].

2.5 Bihar Hairy Caterpillar (*Spilosoma obliqua*)

Spilosoma obliqua (Lepidoptera: Arctiidae) is a polyphagous defoliator known for its voracious feeding habits. The early instar larvae are gregarious and scrape the chlorophyll from the leaf surface, while the later instars disperse and consume entire leaves, leaving only the midribs and main veins (Kotikal, 1982) ^[27]. A single larva can consume a significant amount of foliage during its development. Outbreaks are sporadic but can be devastating, leading to complete defoliation of mulberry plantations and yield losses of up to 25-30% (Manjunath *et al.*, 2005) ^[25]. The hairy nature of the caterpillars provides them with a degree of protection from predators and some contact insecticides. Management requires early detection and removal of egg masses or gregarious young larvae before they disperse throughout the field.

Table 1: Major mulberry pests and their integrated management strategies.

Pest (Scientific Name)	Damage Symptom	Integrated Management Strategies
Tukra Mealybug (<i>Maconellicoccus hirsutus</i>)	Stunted apical shoots, leaf curling and crinkling ("tukra").	Cultural: Pruning and burning of infested shoots. Biological: Release of parasitoid <i>Anagyrus dactylopii</i> and predator <i>Cryptolaemus montrouzieri</i> . Chemical: Spot application of 0.076% Dichlorvos (DDVP) with a safe period of 7 days. Botanical: Spraying of neem oil (3%).
Thrips (<i>Pseudodendrothrips mori</i>)	Silvery-white streaks on leaves; leaves become brittle and coarse.	Cultural: Sprinkler irrigation to dislodge thrips. Biological: Conservation of predatory coccinellids. Chemical: Foliar spray of Fipronil SSC @ 50 g a.i./ha with an appropriate safe period. Botanical: Application of neem-based pesticides.
Spiralling Whitefly (<i>Aleurodicus 188isperses</i>)	Yellowing of leaves; presence of sooty mold on honeydew excretions.	Cultural: Removal and destruction of heavily infested leaves. Use of yellow sticky traps. Biological: Introduction and conservation of parasitoids <i>Encarsia guadeloupae</i> and predator <i>Nephaspis oculatus</i> . Mechanical: Forcible water jetting.
Leaf Roller/Webber (<i>Diaphania pulverulentalis</i>)	Apical leaves rolled or webbed together; larvae feed inside.	Mechanical: Clipping and burning of infested leaf rolls. Cultural: Deep ploughing to expose pupae. Use of light traps for adults. Biological: Release of egg parasitoid <i>Trichogramma chilonis</i> and larval parasitoid <i>Bracon brevicornis</i> . Chemical: Spray of 0.076% DDVP 10 days after pruning.
Bihar Hairy Caterpillar (<i>Spilosoma obliqua</i>)	Gregarious young larvae scrape leaves; older larvae cause complete defoliation.	Mechanical: Collection and destruction of egg masses and gregarious early instar larvae. Biological: Application of <i>Bacillus thuringiensis</i> (Bt) formulations. Chemical: Application of recommended contact insecticides on young larvae.

3. Major Silkworm Pests

In addition to pathogens, silkworms are directly attacked by several insect pests that act as predators or parasitoids, causing significant mortality during the rearing process. These pests are a direct threat to cocoon crop yield and require vigilant management.

3.1 Uzi Fly (*Exorista bombycis*)

The Uzi fly, *Exorista bombycis* (Diptera: Tachinidae), is an endoparasitoid and the most formidable pest of *B. mori* in the Indian subcontinent, causing cocoon crop losses estimated at 10-20% annually (Singh and Saratchandra, 2002) ^[28]. The adult female fly lays one or more eggs on the integument of silkworm larvae, typically from the third to the fifth instar. Upon hatching, the maggot bores into the silkworm's body and feeds on its internal tissues. The parasitized silkworm may continue to grow and even spin a cocoon, but the Uzi fly maggot eventually emerges by piercing the cocoon, rendering it unreelable and worthless. In some cases, the silkworm dies before spinning. The entire life cycle of the fly is short, allowing for multiple generations within a single silkworm rearing season, leading to rapid population build-up (Narasimhanna, 1988) ^[29].

3.2 Dermestid Beetles (*Dermestes* spp.)

Dermestid beetles (Coleoptera: Dermestidae) are primarily storage pests that infest silkworm cocoons, particularly

during storage and processing. Species such as *Dermestes maculatus* and *Dermestes ater* are notorious for causing damage. The adult beetles lay eggs on or near the cocoons and the larvae, upon hatching, bore into the cocoons to feed on the dead pupae inside (Veer *et al.*, 1996) ^[30]. This feeding activity creates holes in the cocoons, cutting the continuous silk filament and making them unsuitable for reeling. The larvae are covered in long setae and are highly mobile. In addition to damaging cocoons, their presence can lead to contamination of the silk. Effective management relies on maintaining strict hygiene in storage facilities and using physical or chemical methods to prevent infestation.

3.3 Predatory Ants

Various species of predatory ants can be a nuisance in silkworm rearing houses, especially in tropical regions. Ants are attracted to the silkworm larvae, particularly during the early instars when they are small and vulnerable. They can invade rearing trays, attack, kill and carry away young larvae, leading to a direct reduction in the silkworm population (Dejean *et al.*, 2025) ^[31]. While not typically causing large-scale crop loss like the Uzi fly, persistent ant infestations can result in significant cumulative losses over time. Management involves physical barriers, such as placing the legs of rearing stands in bowls of water (ant wells) and maintaining cleanliness around the rearing house to eliminate food sources that might attract them.

4. Major Silkworm Diseases

Silkworm diseases are the single most significant factor contributing to crop loss in sericulture worldwide. *Bombyx mori*, having been domesticated for millennia, has lost many of its natural defense mechanisms and is highly susceptible to a range of pathogens. Disease outbreaks are often influenced by environmental conditions, mulberry leaf quality and rearing hygiene.

4.1 Viral Diseases-Grasserie

Grasserie, caused by the *Bombyx mori* nucleopolyhedrovirus (BmNPV), is one of the most common viral diseases. The primary mode of transmission is through ingestion of contaminated mulberry leaves. Once inside the midgut, the virus infects host cells, replicates and spreads systemically. Infected larvae exhibit a swollen, tense and shiny integument due to the accumulation of polyhedral inclusion bodies (PIBs) in the hemolymph, which gives it a milky white appearance (Rohrmann, 2019) [32]. The larvae become sluggish, lose their appetite and eventually, their integument becomes fragile and ruptures easily, releasing the infectious viral fluid and contaminating the rearing environment. High temperature and humidity are known to exacerbate the disease. There is no curative treatment and management relies entirely on strict disinfection and hygiene to prevent the spread of the virus.

4.2 Bacterial and Viral Diseases-Flacherie

Flacherie is a complex syndrome rather than a single disease, characterized by symptoms such as lethargy, loss of appetite, soft and flaccid bodies and often accompanied by diarrhea and vomiting. It can be caused by bacteria (e.g., *Serratia marcescens*, *Bacillus thuringiensis*), viruses (e.g., *B. mori* infectious flacherie virus-BmIFV), or a combination of both (Priyadharshini *et al.*, 2008) [33]. BmIFV is a single-stranded RNA virus that primarily infects the goblet cells of the midgut, leading to digestive dysfunction and secondary bacterial infections (Iwashita, 1971) [34]. The disease is highly contagious and spreads through contaminated leaves and fecal matter. Stress factors such as poor-quality leaves, fluctuating temperatures and inadequate ventilation make silkworms more susceptible to flacherie. Crop losses due to BmIFV can be as high as 40% (Savanurmath *et al.*, 1994)

[35].

4.3 Fungal Diseases-Muscardine

Muscardine is a fungal disease that affects silkworms, with white muscardine, caused by *Beauveria bassiana*, being the most prevalent and destructive (Lu *et al.*, 2021) [9]. Infection occurs when conidia of the fungus land on the silkworm's cuticle, germinate and penetrate the integument. The fungus then proliferates in the hemocoel, consuming nutrients and producing toxins. Initially, infected larvae lose their appetite and become inactive. After death, the body hardens and under humid conditions, the fungus emerges from the body, covering the cadaver with a white, chalky layer of mycelia and conidia, which are then dispersed by air currents to infect other larvae (Feng *et al.*, 1994) [36]. The disease is particularly severe during rainy and winter seasons due to favorable cool and humid conditions (Ghosh *et al.*, 2025) [37]. While *B. bassiana* is a potent biocontrol agent against many insect pests, it is a devastating pathogen for silkworms, highlighting the delicate balance required in sericulture pest management.

4.4 Protozoan Diseases-Pebrine

Pebrine, caused by the microsporidian *Nosema bombycis*, is historically the most feared of all silkworm diseases. It was responsible for nearly collapsing the French silk industry in the 19th century until Louis Pasteur developed a method for its detection and control. The pathogen is unique in its ability to be transmitted both horizontally (through ingestion of spores from contaminated sources) and vertically (Transovarially, from an infected mother moth to her offspring) (Pan *et al.*, 2017) [10]. Infected larvae show irregular growth, loss of appetite and may exhibit black, pepper-like spots on their integument, which gives the disease its name. The parasite multiplies within host cells, affecting various tissues including the midgut, silk glands and reproductive organs. Vertical transmission makes pebrine particularly insidious, as it can perpetuate the disease across generations. Management is entirely preventive and relies on the strict microscopic examination of mother moths after egg-laying to ensure that only eggs from disease-free moths (known as "cellular rearing") are used for the next crop (Bhat and Nataraju, 2005) [38].

Table 2: Major silkworm diseases, their causal organisms and key symptoms.

Disease	Causal Organism	Key Symptoms and Transmission
Grasserie (Nuclear Polyhedrosis)	<i>Bombyx mori</i> nucleopolyhedrovirus (BmNPV)	Symptoms: Swollen, shiny integument; sluggishness; body ruptures easily, releasing milky white hemolymph filled with polyhedra. Transmission: Per-oral, through ingestion of contaminated mulberry leaves.
Flacherie	Bacteria (e.g., <i>Serratia</i> spp., <i>Bacillus</i> spp.) and/or <i>B. mori</i> infectious flacherie virus (BmIFV)	Symptoms: Larvae become soft, flaccid and dark-colored; loss of appetite, vomiting, diarrhea; high mortality. Transmission: Per-oral, through contaminated leaves and rearing environment. Stress factors are predisposing.
Muscardine (White)	<i>Beauveria bassiana</i> (Fungus)	Symptoms: Loss of appetite, cessation of growth; body becomes hard and mummified after death. Under humid conditions, a white fungal mycelium covers the cadaver. Transmission: Cuticular, via airborne conidia.
Pebrine	<i>Nosema bombycis</i> (Microsporidian/Protozoan)	Symptoms: Irregular growth, sluggishness, poor appetite; characteristic black, pepper-like spots on the integument. Transmission: Per-oral (horizontal) and transovarial (vertical, from mother moth to egg), making it highly insidious.

5. Principles of Integrated Pest and Disease Management (IPDM)

Integrated Pest and Disease Management (IPDM) in sericulture is an ecological approach that seeks to manage pests and pathogens by combining multiple control tactics in a compatible manner. It moves away from a reactive, chemical-dependent model to a proactive, knowledge-based system that prioritizes long-term sustainability. The fundamental principles of IPDM are rooted in understanding the agroecosystem and using this knowledge to minimize pest and disease impact while reducing economic and environmental risks.

A core principle is ecological pest regulation, which involves leveraging natural processes to suppress pest populations. This includes the conservation and augmentation of natural enemies (predators and parasitoids) that are already present in and around mulberry fields (Lalitha *et al.*, 2018) ^[20]. Practices such as maintaining diverse vegetation around fields can provide alternative food sources and shelter for these beneficial organisms, enhancing their effectiveness. Understanding the tri-trophic interactions between the mulberry plant, herbivorous pests and their natural enemies is crucial for designing effective ecological strategies (Price *et al.*, 1980) ^[39].

Another key principle is the use of economic threshold levels (ETLs). An ETL is the pest density at which management action should be taken to prevent an increasing pest population from reaching the economic injury level (EIL), the point where the cost of control is equal to the value of the crop loss. In sericulture, this concept is applied to both mulberry pests and silkworm diseases. Regular monitoring or “scouting”; of mulberry fields and rearing houses is essential to determine pest and disease incidence (Etebari and Bizhannia, 2006) ^[40]. Decisions to intervene are based on these data-driven thresholds rather than a fixed calendar schedule, ensuring that control measures are applied only when necessary, thus reducing costs and environmental impact (Stern *et al.*, 1959) ^[41].

Ecosystem-based management is a holistic view that considers the entire sericulture production system—from soil health to rearing house environment—as an interconnected unit. Healthy soil promotes vigorous mulberry growth, making plants more resilient to pest attacks (Shashidhar *et al.*, 2018) ^[42]. Similarly, maintaining optimal temperature and humidity in the rearing house not only supports silkworm growth but also creates an environment less conducive to pathogens like *B. bassiana* (Ghosh *et al.*, 2025) ^[37]. This principle emphasizes that management practices in one part of the system can have significant effects on others.

Preventive sanitation is arguably the most critical principle in silkworm disease management. Since curative treatments for most silkworm diseases are unavailable, prevention is the only viable strategy. This involves a strict regimen of cleaning and disinfecting the rearing house and all equipment between rearing cycles using effective disinfectants like formalin or bleaching powder (Singh and Saratchandra, 2002) ^[28]. Ensuring a clean, disease-free environment from the start of rearing is fundamental to preventing outbreaks. This extends to mulberry field hygiene, such as the removal and destruction of infested plant parts to reduce the inoculum of pests like the leaf roller (Islam *et al.*, 2025) ^[6].

Finally, the principle of compatibility of control strategies ensures that the different tactics used in an IPDM program do not conflict with one another. For example, if biological control agents are being released, the use of broad-spectrum chemical pesticides must be avoided as they would kill the beneficial insects along with the pests (Sakthivel and Qadri, 2010b) ^[43]. Similarly, the choice of a botanical insecticide should be based on its efficacy against the target pest and its safety for both silkworms and natural enemies. The successful integration of multiple tactics requires careful planning and a deep understanding of the interactions between each component of the management strategy.

6. Biological Control Strategies in Sericulture

Biological control, the use of living organisms to suppress pest populations, is a cornerstone of sustainable IPDM in sericulture. It offers an environmentally sound alternative to chemical pesticides by harnessing natural predator-prey, parasitoid-host and pathogen-host relationships. These strategies are highly specific and pose minimal risk to silkworms, humans and the environment.

6.1 Parasitoids

Parasitoids are insects that lay their eggs in or on a host, with the developing larvae consuming and eventually killing the host. They are highly effective due to their host specificity and searching ability. In sericulture, the most widely utilized parasitoids belong to the genus *Trichogramma*. *Trichogramma chilonis*, an egg parasitoid, is mass-reared and released in mulberry fields to control lepidopteran pests like the leaf roller, *D. pulverulentalis* (Kumar *et al.*, 2024) ^[44]. The tiny wasp lays its eggs inside the pest's eggs, preventing them from hatching and thus providing control before any damage to the crop occurs (Smith, 1996) ^[45]. Other parasitoids, such as the larval parasitoid *Bracon brevicornis* and the pupal parasitoid *Tetrastichus howardii*, have also shown efficacy against leaf rollers (Islam *et al.*, 2025) ^[6]. For the control of the tukra mealybug, parasitoids like *Anagyrus dactylopii* have been successfully used in classical biological control programs (Mani, 1989) ^[16].

6.2 Entomopathogenic Fungi

Entomopathogenic fungi are microorganisms that cause disease in insects. They are particularly effective against sap-sucking pests and those with protective coatings. The two most important fungi used in pest management are *Beauveria bassiana* and *Metarhizium anisopliae*. While *B. bassiana* is a lethal pathogen of silkworms, specific strains have been developed and commercialized for use against pests like whiteflies, thrips and mealybugs in various crops (Reay-Jones *et al.*, 2022) ^[46]. The application requires careful timing to avoid any risk to silkworms, often with a prescribed safe period before leaf harvest. *Metarhizium anisopliae* is effective against a wide range of pests, including soil-dwelling insects. It infects the host upon contact, penetrates the cuticle and multiplies within the insect's body (Roberts and St. Leger, 2004) ^[47]. The use of these fungi as biopesticides is a growing area of research, focusing on strain selection, formulation and application methods to maximize efficacy against pests while ensuring safety for *B. mori*.

6.3 Bacterial Agents

Bacillus thuringiensis (Bt) is a naturally occurring soil bacterium that produces crystalline proteins (Cry toxins) that are toxic to specific groups of insects. It is the most successful microbial insecticide used globally. When ingested by a susceptible insect, such as a lepidopteran larva, the Cry toxins are activated in the alkaline environment of the midgut, where they bind to specific receptors on the gut wall, creating pores and leading to cell lysis, gut paralysis and eventual death of the insect (Bravo *et al.*, 2007) [48]. Bt formulations are highly specific, with different strains targeting different insect orders (e.g., Lepidoptera, Coleoptera, Diptera). In sericulture, Bt is used to control defoliating caterpillars like the leaf roller and Bihar hairy caterpillar. A key advantage is its safety for most non-target organisms, including humans and beneficial insects. However, its efficacy can be reduced by UV radiation and resistance has been reported in some pest populations, necessitating careful management.

6.4 Microbial Antagonists

In addition to controlling insect pests, microorganisms are also being explored for the management of silkworm pathogens. This involves the use of beneficial microbes that can outcompete or inhibit the growth of pathogens. Strains of *Bacillus velezensis* have been identified that produce a range of antifungal and antibacterial compounds, such as surfactin, fengycin and iturin (Liu *et al.*, 2025) [49]. These lipopeptides can disrupt the cell membranes of pathogenic fungi and bacteria. Research is underway to use these beneficial bacteria as probiotics in silkworm rearing or as disinfectants for rearing environments. By colonizing the silkworm gut or the rearing surfaces, these antagonists can create a protective barrier, reducing the chances of infection by pathogens like those causing flacherie or muscardine. This approach represents a novel frontier in silkworm disease management, moving towards a more biologically-based sanitation system.

Table 3: Key biological control agents (BCAs) used in sericulture IPDM.

BCA Type	Agent	Target Pest(s)	Mode of Action
Parasitoids	<i>Trichogramma chilonis</i>	Leaf roller (<i>D. pulverulentalis</i>) and other lepidopteran pests	Egg parasitoid; lays eggs inside pest eggs, preventing hatching.
	<i>Anagyrus dactylopii</i>	Tukra mealybug (<i>M. hirsutus</i>)	Endoparasitoid of mealybug nymphs and adults.
Predators	<i>Cryptolaemus montrouzieri</i>	Mealybugs	Both larvae and adults are voracious predators of mealybug eggs, nymphs and adults.
	Lacewings (<i>Chrysoperla</i> spp.)	Thrips, aphids, whiteflies, mealybugs	Larvae ("aphid lions") are generalist predators with a wide prey range.
Entomopathogenic Fungi	<i>Beauveria bassiana</i> (specific strains)	Whiteflies, thrips, mealybugs	Infects through the cuticle, causing mycosis. Use requires care due to pathogenicity to silkworms.
	<i>Metarhizium anisopliae</i>	Soil-dwelling pests, beetles	Contact pathogen that penetrates the insect exoskeleton.
Entomopathogenic Bacteria	<i>Bacillus thuringiensis</i> (Bt)	Lepidopteran larvae (e.g., leaf roller, hairy caterpillar)	Stomach poison; Cry toxins ingested by larvae destroy the midgut lining.
Microbial Antagonists	<i>Bacillus velezensis</i>	Silkworm pathogens (fungal and bacterial)	Produces antimicrobial lipopeptides (surfactin, fengycin) that inhibit pathogen growth. Used as a probiotic or disinfectant.

7. Botanical and Eco-Friendly Pest Control

Botanical insecticides, derived from plants, offer a biodegradable and often less toxic alternative to synthetic chemicals. They are generally considered more compatible with IPDM programs due to their lower persistence and reduced impact on non-target organisms. Their complex mixture of active compounds can also delay the development of resistance in pests.

7.1 Neem-Based Pesticides (*Azadirachta indica*)

The neem tree, *Azadirachta indica*, is the most widely recognized source of botanical pesticides. Its seeds contain a complex of over 100 bioactive compounds known as limonoids, with azadirachtin being the most potent (Isman, 2006) [50]. Azadirachtin does not cause immediate knockdown but acts as a powerful antifeedant, growth regulator and sterilant. It disrupts the insect endocrine system by interfering with the synthesis of ecdysone, the molting hormone, thereby preventing larvae from molting and developing into adults (Mordue (Luntz) and Blackwell, 1993) [51]. Neem oil and neem seed kernel extract (NSKE) are effective against a broad spectrum of pests, including mealybugs, thrips, whiteflies and caterpillars. In sericulture, commercial neem formulations (0.03% AZ) are recommended for controlling mulberry pests, with a safe period of 7-10 days before leaves can be fed to silkworms to avoid any adverse effects (Islam *et al.*, 2025) [6]. The multi-

modal action of neem makes it a valuable tool for resistance management.

7.2 Other Plant-Derived Extracts and Oils

Besides neem, extracts from various other plants have shown insecticidal properties against mulberry pests. Aqueous leaf extracts of plants like *Catharanthus roseus* (periwinkle), *Piper betle* (betel leaf) and *Lantana camara* have demonstrated efficacy against leaf roller larvae (Maheswari and Govindaiah, 2017) [53]. Essential oils from plants such as eucalyptus, citronella and mint can act as repellents or fumigants. These botanicals often contain a cocktail of compounds like alkaloids, terpenes and phenols that can be toxic or deterrent to insects. While many of these have shown promise in laboratory studies, their field efficacy, standardization of active ingredients and appropriate application methods require further research to be integrated into practical sericulture IPDM programs (Ravikumar *et al.*, 2012) [54].

7.3 Semiochemicals and Pheromone Traps

Semiochemicals are signaling chemicals used by insects to communicate. Pheromones, a type of semiochemical, are used for mate location. Synthetic versions of these pheromones can be used in traps for monitoring pest populations or for mass trapping to reduce their numbers. Pheromone traps for lepidopteran pests like the leaf roller

can help in early detection of adult moth activity, allowing for precise timing of control measures (Witzgall *et al.*, 2010) ^[55]. Light traps are also used to attract and kill the adult moths of nocturnal pests like *D. pulverulentalis*. Yellow sticky traps are effective for monitoring and mass trapping sap-sucking insects like whiteflies and thrips, which are attracted to the yellow color. These trapping methods are non-toxic and highly specific, making them excellent components of an IPDM strategy.

8. Cultural and Preventive Management Practices

Cultural and preventive practices are the foundation of any successful IPDM program. They are proactive measures designed to create an environment that is unfavorable for pest and pathogen development while promoting the health of the crop and silkworms. These low-cost, traditional methods are crucial for minimizing the need for direct control interventions.

8.1 Rearing House Sanitation and Disinfection

Strict sanitation is the first line of defense against silkworm diseases. Before the start of a new rearing batch, the rearing house and all equipment (trays, stands, nets) must be thoroughly cleaned to remove any organic debris from the previous crop. This is followed by disinfection to eliminate any lingering pathogen spores. A 2% formalin solution is a commonly used and effective disinfectant, but it requires a long airing period due to its toxicity. Other recommended disinfectants include bleaching powder solution and commercially available formulations like 'Vijetha', which is a mixture of slaked lime and bleaching powder (Dandin *et al.*, 2003) ^[56]. Proper disinfection breaks the disease cycle between crops and is fundamental for preventing outbreaks of pebrine, grasserie and muscardine.

8.2 Mulberry Field Hygiene

Maintaining hygiene in the mulberry field is equally important for managing both pests and diseases. This includes the regular removal and destruction of weed hosts that may harbor pests. Infested plant parts, such as tukra-affected shoots or leaves webbed by leaf rollers, should be pruned and burned to reduce the pest population and inoculum load (Islam *et al.*, 2025) ^[6]. After pruning, deep ploughing of the field can expose and kill the pupae of pests like the leaf roller that pupate in the soil. Flood irrigation, where feasible, can also help in destroying soil-dwelling pupae. These practices disrupt the life cycles of pests and reduce their carryover from one season to the next.

8.3 Environmental Regulation

The growth of silkworms and the proliferation of their pathogens are highly sensitive to environmental conditions. Maintaining optimal temperature (25-28 °C) and relative humidity (70-85%, varying with larval stage) is critical for healthy larval development and for suppressing disease (Rahmathulla, 2012) ^[57]. High humidity and low temperatures favor the development of white muscardine, while high temperatures can be a stressor that predisposes silkworms to flacherie. Proper ventilation in the rearing house is essential to remove excess moisture and harmful gases like ammonia and carbon dioxide. Using heaters, coolers, humidifiers and exhaust fans to regulate the microenvironment is a key preventive measure against disease outbreaks.

8.4 Bed Disinfectants

During the rearing period, bed disinfectants are applied to the silkworm rearing beds to control the spread of pathogens that may be introduced with mulberry leaves or through other means. These are typically lime-based powders mixed with a mild disinfectant. They are dusted over the larvae after each molt and before they resume feeding. The lime helps to keep the bed dry, creating an unfavorable condition for fungal and bacterial growth, while the disinfectant component kills spores on the larval body and in the bed (Vijaya Kumari, 2014) ^[58]. Commonly used bed disinfectants include 'Resham Keet Oushadh' (RKO) and 'Vijetha Green'. This practice is a simple yet effective way to suppress the horizontal transmission of diseases within the rearing tray.

9. Molecular and Biotechnological Approaches

Advances in molecular biology and biotechnology are providing powerful new tools for pest and disease management in sericulture. These approaches offer high specificity, efficiency and the potential to overcome some of the limitations of conventional methods.

9.1 Molecular Diagnostics of Pathogens

Rapid and accurate diagnosis of silkworm diseases is crucial for timely intervention and preventing widespread crop loss. Traditional diagnostic methods, such as microscopic examination for pebrine, can be time-consuming and require expertise. Molecular techniques based on Polymerase Chain Reaction (PCR) offer a highly sensitive and specific alternative. PCR-based assays have been developed for the detection of major pathogens, including BmNPV, BmIFV and *Nosema bombycis* (Pan *et al.*, 2017) ^[10]. These methods can detect pathogens even at very low levels of infection, long before visible symptoms appear. For instance, specific primers targeting the fungal genome can confirm the presence of *B. bassiana* or *M. anisopliae* in infected tissues (Castrillo *et al.*, 2003) ^[59]. The development of quantitative PCR (qPCR) allows for the quantification of pathogen load, which can help in assessing disease severity. These diagnostic tools are invaluable for disease surveillance, epidemiological studies and for certifying disease-free silkworm eggs.

9.2 RNA Interference (RNAi) for Pest Suppression

RNA interference (RNAi) is a natural biological process of gene silencing triggered by double-stranded RNA (dsRNA). This mechanism has been harnessed as a novel strategy for pest control, offering unprecedented specificity (Niu *et al.*, 2024) ^[60]. By designing dsRNA molecules that are complementary to the mRNA of an essential gene in a target pest, it is possible to silence that gene, leading to developmental defects or mortality. The major challenge in lepidopteran insects like the silkworm and its pests has been the efficient delivery of dsRNA, as naked dsRNA is often degraded by nucleases in the insect gut (Terenius *et al.*, 2011) ^[61]. However, recent breakthroughs have shown that encapsulating dsRNA in nanoparticles, such as those made from chitosan, can protect it from degradation and facilitate its uptake, enabling successful oral RNAi in *B. mori* (Liu *et al.*, 2025) ^[62]. This technology holds immense promise for developing highly specific "biopesticides"; that target key pests of mulberry, such as the leaf roller or mealybug,

without harming the silkworm or any other non-target organisms.

9.3 Development of Resistant Mulberry and Silkworm Strains

Breeding for resistance is one of the most sustainable strategies for pest and disease management. Molecular markers, such as Inter-Simple Sequence Repeats (ISSR) and Sequence-Related Amplified Polymorphism (SRAP), are being used to assess the genetic diversity within mulberry germplasm and identify genotypes with desirable traits, including resistance to pests and diseases (Zhang *et al.*, 2019) ^[63]. This allows for more targeted and efficient breeding programs. On the silkworm side, genomic studies are helping to identify genes associated with disease resistance. For example, quantitative trait loci (QTL) mapping has identified genomic regions linked to resistance against BmNPV (Abe *et al.*, 2004) ^[64]. Furthermore, whole-genome sequencing of different silkworm strains and their pathogens is providing insights into the molecular basis of host-pathogen interactions (Pan *et al.*, 2017) ^[10]. This knowledge can be used to breed silkworm strains with enhanced immunity, for example, by selecting for variants of immune-related genes like hemocytin that confer resistance to *N. bombycis* (Ni *et al.*, 2020) ^[65].

9.4 Genomic Studies of Silkworm Pathogens

The sequencing of genomes of major silkworm pathogens has opened new avenues for understanding their biology and identifying novel control targets. The genome of *N. bombycis*, for instance, reveals a highly reduced metabolic capacity, indicating its complete dependence on the host for energy and nutrients (Pan *et al.*, 2013) ^[66]. This reliance on host metabolism presents potential targets for intervention. Transcriptomic and proteomic studies of infected silkworms have revealed how pathogens like *N. bombycis* and *B. bassiana* manipulate host physiology, including hijacking metabolic pathways and suppressing immune responses (Hu *et al.*, 2021; Lu *et al.*, 2021) ^[8, 9]. Databases like SilkPathDB have been created to consolidate this genomic, transcriptomic and proteomic data, providing a comprehensive resource for researchers to study silkworm-pathogen systems and develop new anti-pathogen strategies (Pan *et al.*, 2017) ^[10].

10. Digital and Precision Sericulture Technologies

The integration of digital technologies, including Artificial Intelligence (AI), the Internet of Things (IoT) and remote sensing, is ushering in an era of “smart sericulture.” These tools enable precision management of both mulberry cultivation and silkworm rearing, leading to increased efficiency, reduced losses and enhanced sustainability.

10.1 AI-Based Pest and Disease Detection

Artificial Intelligence, particularly machine learning and deep learning algorithms, is being applied for the automated detection of pests and diseases. AI models, such as Convolutional Neural Networks (CNNs), can be trained on large datasets of images to identify visual symptoms of diseases on mulberry leaves (e.g., leaf spot, powdery mildew) or signs of pest infestation with high accuracy (Vijayareddy *et al.*, 2023) ^[67]. Similarly, AI-powered image analysis can detect diseases in silkworms or abnormalities in their growth. Recently, researchers have explored using

sound analytics to detect pests in agricultural fields; an AI-enabled system can be trained to recognize the specific sound signatures of pests, providing a real-time, non-invasive monitoring tool (Ali *et al.*, 2024) ^[68]. These systems, often deployed via smartphone apps, can provide farmers with early warnings, enabling timely and targeted interventions.

10.2 IoT-Based Monitoring and Automation

The Internet of Things (IoT) involves a network of interconnected sensors that collect and transmit data in real-time. In sericulture, IoT sensors can be deployed in rearing houses to continuously monitor critical environmental parameters like temperature, humidity, light and air quality (Gowda *et al.*, 2021) ^[69]. This data is sent to a central system, which can automatically activate controllers (heaters, humidifiers, fans) to maintain optimal conditions, reducing manual labor and ensuring a stable environment for silkworm growth (Shilpa *et al.*, 2025) ^[70]. In mulberry fields, IoT-based soil sensors can monitor moisture and nutrient levels, enabling precision irrigation and fertilization, which optimizes resource use and promotes plant health (Su *et al.*, 2024) ^[71].

10.3 Predictive Disease and Yield Models

By combining historical data with real-time information from IoT sensors, AI-driven predictive models can forecast the likelihood of disease outbreaks. These models analyze patterns in environmental data (e.g., a specific combination of temperature and humidity) that are known to precede disease incidence, providing farmers with advance warnings to implement preventive measures (Sharma and Verma, 2021) ^[72]. Predictive analytics can also be used to forecast silkworm growth rates and potential cocoon yield based on the quality of mulberry leaves and rearing conditions. This allows for better planning and resource management, helping to stabilize production and improve economic returns for farmers.

11. Challenges and Research Gaps

Despite significant progress in developing sustainable IPDM strategies, several challenges and research gaps hinder their widespread adoption and effectiveness in sericulture.

A primary challenge is the potential for resistance development in both pests and pathogens. Just as pests can develop resistance to chemical insecticides, they can also adapt to biological control agents. For example, some insect populations have evolved resistance to Bt toxins (Tabashnik *et al.*, 2008) ^[73]. Similarly, pathogens may develop resistance to disinfectants or antimicrobial agents. Continuous monitoring for resistance and the development of strategies to manage it, such as rotating control methods or using multiple tactics with different modes of action, are essential.

There is a significant gap between laboratory success and field validation of biocontrol agents. While many parasitoids and entomopathogens show high efficacy under controlled laboratory conditions, their performance in the field can be variable and is often influenced by environmental factors like temperature, humidity and UV radiation (Lacey *et al.*, 2015) ^[74]. More large-scale field trials are needed to determine the optimal release rates, application timings and formulations for different agro-climatic zones. Furthermore, the cost and logistics of mass-producing and delivering

these live agents can be a barrier for small-scale farmers.

Climate change poses a growing threat to sericulture by altering pest and disease dynamics. Rising temperatures can accelerate the life cycles of pests, leading to more generations per year and expanded geographical ranges. Changes in rainfall patterns can affect the incidence of fungal diseases like muscardine. Research is needed to model the potential impacts of climate change on key sericultural pests and diseases and to develop climate-resilient IPDM strategies (Sujatha *et al.*, 2024) ^[75].

Finally, socio-economic barriers to adoption among farmers remain a major hurdle. Many farmers, particularly in developing regions, may lack the knowledge, training, or financial resources to implement complex IPDM programs. There is often a preference for the perceived simplicity and rapid action of chemical pesticides. Effective extension services, farmer training programs and policies that incentivize the adoption of sustainable practices are crucial to bridge this gap between research and on-the-ground implementation (Parsa *et al.*, 2014) ^[76].

12. Future Prospects

The future of pest and disease management in sericulture lies in the integration of cutting-edge science with ecological principles to create highly resilient and productive systems. Several emerging innovations are poised to transform the industry.

Microbiome engineering represents a novel frontier for disease control. The silkworm gut and the mulberry phyllosphere host complex communities of microbes, some of which can be beneficial. Research is moving towards identifying and manipulating these microbiomes to enhance disease resistance. This could involve introducing probiotic bacteria to the silkworm diet to inhibit gut pathogens or applying beneficial microbes to mulberry leaves to outcompete foliar pathogens (Unni *et al.*, 2012) ^[77]. This approach aims to bolster the natural defenses of both the plant and the insect.

The development of climate-smart sericulture systems will be critical for adapting to a changing environment. This involves integrating climate forecasting with pest and disease models to create early warning systems. It also includes breeding mulberry and silkworm varieties that are more tolerant to heat and drought stress and developing agronomic practices that conserve water and improve soil health, making the entire system more resilient to climatic variability.

Digital pest surveillance networks, powered by AI and IoT, will become more sophisticated. Imagine a network where farmers can upload images of pests or diseased leaves from their smartphones, which are instantly identified by an AI system. This data, aggregated over large geographical areas, can be used to track the spread of pests and diseases in real-time, enabling coordinated, landscape-level management responses (Ali *et al.*, 2024) ^[68].

Ultimately, the goal is to move towards fully sustainable silk production models that are not only economically viable but also ecologically sound and socially equitable. This will require a multi-stakeholder approach, involving researchers, extension workers, policymakers and farmers, to co-create and implement IPDM strategies that are tailored to local conditions and needs, ensuring the long-term health and prosperity of the global silk industry.

13. Conclusion

The sustainability of the global sericulture industry is fundamentally dependent on the effective management of a complex web of pests and diseases that threaten both mulberry crops and the silkworm, *Bombyx mori*. The historical reliance on chemical interventions has proven to be a short-sighted strategy, fraught with risks to the environment, non-target organisms and the very silkworms the industry seeks to protect. The adoption of an Integrated Pest and Disease Management (IPDM) framework is not merely an alternative but an imperative for the long-term viability of sericulture.

This review has synthesized the extensive body of research demonstrating the power of integrating multiple, compatible control tactics. The foundation of a robust IPDM program lies in preventive cultural practices, such as stringent sanitation and environmental regulation, combined with ecological strategies that conserve and augment natural enemies. The targeted application of biological control agents, including parasitoids, entomopathogens and bacterial insecticides, offers potent and specific solutions with minimal ecological disruption. These are complemented by the judicious use of biodegradable botanical pesticides, such as those derived from neem.

Looking forward, the fusion of biotechnology and digital innovation promises to revolutionize sericulture. Molecular diagnostics, RNAi-based biopesticides and marker-assisted breeding are providing unprecedented precision and efficacy in pest and disease control. Simultaneously, AI and IoT-powered tools are enabling a shift towards data-driven, precision sericulture that optimizes resource use and minimizes losses. By embracing this holistic, multi-pronged approach, the sericulture industry can navigate the challenges of resistance, climate change and economic pressures. The continued commitment to research, extension and farmer education will be paramount in translating these scientific advancements into practical, sustainable solutions that ensure the production of the “Queen of Textiles” for generations to come.

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