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Anna Kaushik
Research Scholar, Department of Sericulture, Forest College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Dr. P Priyadharshini
Assistant Professor, Department of Sericulture, Forest College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Bidisha Saikia
Research Scholar, Department of Agricultural Biotechnology, Assam Agricultural University, Jorhat, Assam, India

Manihar Talukdar
Research Scholar, School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya, India

Navneet Mondal
Research Scholar, Department of Entomology, Post Graduate College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Samastipur, Bihar, India

Akash A
Research Scholar, Department of Agriculture, Kalasalingam School of Agriculture and Horticulture, Kalasalingam Academy of Research and Education, Anand Nagar, Krishnankoil, Tamil Nadu, India

Corresponding Author:
Dr. P Priyadharshini
Assistant Professor, Department of Sericulture, Forest College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Botanical pesticides and green formulations safe for silkworm rearing

Anna Kaushik, P Priyadharshini, Bidisha Saikia, Manihar Talukdar, Navneet Mondal and Akash A

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Abstract
Silkworm rearing relies heavily on the quality and safety of host plant leaves, yet increasing pesticide use in sericulture landscapes has raised concerns about residues that compromise larval health, cocoon yield, and silk quality. Conventional chemical pesticides, though effective against pests and diseases, persist as residues, disrupt silk gland function, and reduce cocoon market value. This review highlights the growing potential of botanical pesticides and green formulations, such as essential oils, plant extracts, nanoemulsions, biopolymer carriers, and microbial combinations, as safer alternatives. These approaches provide eco-friendly pest suppression while reducing residue persistence, minimizing sublethal impacts on silkworm physiology, and supporting sustainable production. Evidence from laboratory and field trials demonstrates their capacity to control pests like defoliators, sap-sucking insects, and fungal pathogens, though dose sensitivity, variability in composition, and sublethal effects on silk yield remain challenges. Recent advances in formulation technologies enhance efficacy and safety through controlled release, improved stability, and targeted delivery. Adoption barriers, including higher costs, limited availability, and regulatory gaps, require supportive policies, demonstration-based extension, and standardized safety testing that includes silk production endpoints. By synthesizing current knowledge, this review identifies both opportunities and research priorities for integrating botanical pesticides and green formulations into sericulture, aiming to balance pest management, silkworm health, and sustainable silk production.

Keywords: Botanical pesticides, green formulations, nanoemulsions, biopolymer carriers, silkworm rearing

Introduction

Silkworm rearing depends critically on the quality of the leaves it consumes, since leaf nutritional profile (proteins, carbohydrates, vitamins, minerals) and absence of harmful residues determine larval growth, cocoon yield, and silk quality [1, 2]. Poor leaf quality, whether from suboptimal nutrient status or chemical contamination, leads to slower development, increased disease susceptibility, lower effective rate of rearing, and reduced filament strength [2, 3].

Over the past decade, there has been increasing reliance on chemical pesticides in adjacent or intercropped fields, drift, and direct application to foliage to control diverse pests. Chemicals like neonicotinoids, organophosphates, pyrethroids, and others leave residues on leaves or in soil, which are subsequently ingested by silkworm larvae. Several studies document that even sublethal doses of such residues can delay larval growth, reduce cocoon weight, impair silk quality, and cause non-spinning syndromes or larval mortality [3, 4, 5]. Histopathological alterations in vital tissues, including the midgut and silk glands, have been observed following exposure to low doses of insecticides like chlorfenapyr and acetamiprid [3, 5].

These adverse effects raise an urgent need for safer and eco-friendly pest management that ensures pest control without compromising silkworm health. Botanical (plant-derived) pesticides, plant essential oils, extract-based formulations, and green formulations (e.g. reduced dosage, nano-carriers, encapsulation) are receiving growing attention as alternatives to synthetic pesticides [1, 6]. These alternatives may offer lower residue persistence, fewer side-effects, and better compatibility with silkworm physiology while maintaining adequate pest suppression.

This review examines the use of botanical pesticides and green formulations in silkworm rearing, emphasizing approaches that control pests while minimizing adverse effects on larval health and silk productivity. It highlights the different botanical sources, evaluates their effectiveness against common pests, and considers their potential effects on larval growth, cocoon yield, and silk quality. In addition, the review discusses practical aspects such as optimal application methods, safety intervals, and challenges related to adoption and regulatory compliance. By synthesizing current knowledge, it aims to identify key gaps and opportunities for integrating green pest management strategies into sustainable silkworm production systems. An overview of the role of botanical pest management in silkworm rearing is illustrated in Figure 1.

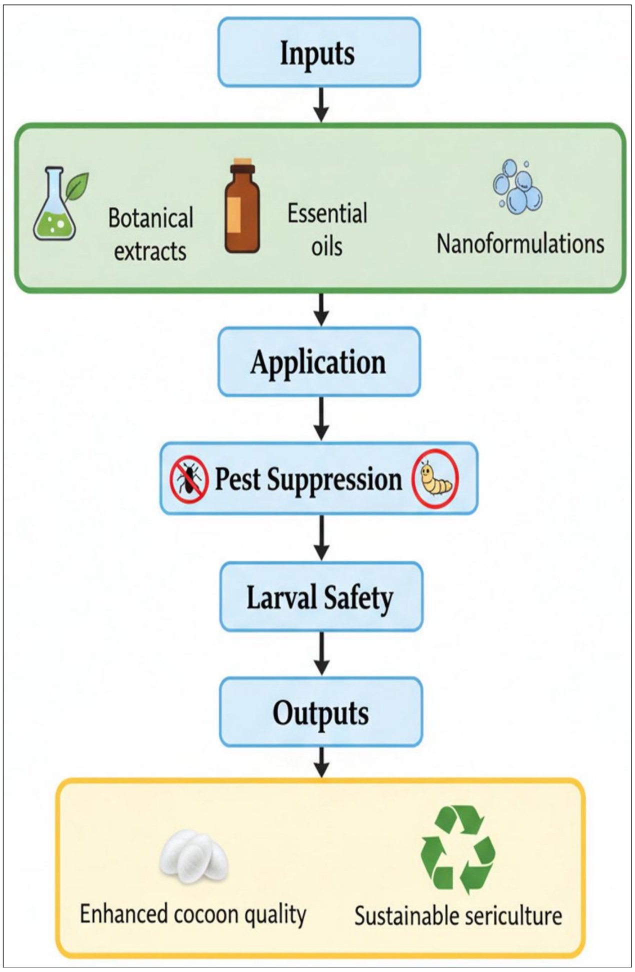

Fig 1: Botanical pest management flowchart in silkworm rearing

Pest and disease challenges in host plant systems for silkworm rearing

The productivity and sustainability of sericulture depend largely on the health and availability of foliage provided to silkworms. A wide range of insect pests, pathogens, and abiotic stress factors influence the quality of host plants and, consequently, the growth and silk yield of silkworms. Among insect pests, defoliators such as leaf rollers (*Diaphania pulverulentalis* and *Glyphodes pyloalis*) are widely reported in Asia and other sericulture regions. They damage leaves by rolling and feeding inside protected folds, leading to considerable reduction in usable biomass for larval feeding [7]. Sap-sucking pests, including thrips (*Pseudodendrothrips mori*), aphids, mealy bugs, and jassids, feed by extracting cell sap, resulting in chlorosis, stunted leaf growth, curling, and reduced photosynthetic efficiency [8, 9]. Infestations of whiteflies also cause sooty mold development on leaf surfaces, lowering palatability and digestibility for silkworms. Root and shoot feeders such as cutworms and termites contribute additional stress by weakening the plant base, thereby reducing the leaf yield over multiple harvests [10].

Pathogens present another major challenge. Fungal diseases, including leaf spot caused by *Bipolaris sorokiniana* and *Curvularia lunata*, powdery mildew, and rust, are frequently recorded and can reduce green leaf area by more than half in severe outbreaks [11]. These infections reduce nutrient assimilation, accelerate senescence, and cause premature leaf drop. In addition, bacterial blight and wilt diseases interfere with vascular tissue and leaf expansion, further lowering overall biomass. The combined incidence of fungal and bacterial pathogens directly affects the nutritional quality of foliage, which is critical for maintaining silkworm growth and cocoon yield. Studies indicate that disease incidence may reach 70–80% in certain germplasm or production systems, highlighting the scale of the threat [7, 11].

Conventional approaches for managing these pests and pathogens have relied heavily on synthetic insecticides and fungicides, such as organophosphates, neonicotinoids, and triazole fungicides. These compounds can effectively suppress pest populations in the short term [10, 12]. However, they also pose significant risks in the context of sericulture. Residues on leaves may persist beyond the harvest interval, leading to ingestion by silkworm larvae and subsequent physiological damage. Even low residue concentrations can alter larval growth, reduce silk gland development, and lower cocoon weight [3, 5]. Sublethal effects include delayed pupation, reduced effective rearing rates, and histopathological alterations of midgut tissues [3, 4]. In addition, broad-spectrum applications can reduce populations of natural enemies such as coccinellids and parasitoids, undermining ecological balance [12]. Overuse also accelerates resistance development in pest populations, making management increasingly difficult over time [10].

These limitations underscore the urgency of exploring alternative strategies. Climatic variability, including rising temperatures, erratic rainfall, and higher humidity, further intensifies pest and disease outbreaks, complicating chemical control regimes [5, 7]. Moreover, increasing regulatory restrictions on pesticide use, coupled with consumer preference for eco-labeled silk products, push the industry toward more sustainable pest management. For sericulture to remain economically viable and environmentally safe, it is essential to reduce reliance on chemical pesticides and instead integrate botanical pesticides, essential oils, microbial formulations, and other green solutions that align with the ecological requirements of silkworm rearing.

Botanical agents: Sources, constituents, and efficacy

Botanical pesticides are gaining traction in sericulture as eco-friendly alternatives to synthetic insecticides. These plant-based formulations are rich in bioactive compounds like terpenoids, flavonoids, alkaloids, limonoids, saponins, and essential oils. These compounds disrupt insect growth, feeding, and reproduction. Unlike conventional pesticides, botanical agents degrade quickly in the environment, reducing residue accumulation and minimizing harm to non-target organisms, including silkworms, when applied judiciously [13, 14].

Sources and Phytochemical Constituents

Neem: Neem (*Azadirachta indica*) is a well-known botanical pesticide. Its seeds and leaves contain azadirachtin, salannin, and other limonoids that disrupt hormonal regulation in insects, leading to molting inhibition, reduced feeding, and compromised reproduction. These effects make neem a natural growth regulator with broad efficacy against Lepidopteran pests, though sensitivity of silkworm larvae varies by developmental stage [1, 15].

Pongamia: *Pongamia pinnata* produces oil rich in karanjin and pongamol, compounds with insecticidal and antifeedant properties. Research has also revealed the presence of phenolic acids, flavonoids, and tannins in its extracts, all of which enhance its bioefficacy as a green pesticide [16, 17].

Garlic: Garlic *(Allium sativum)* offers another important source, with sulfur compounds such as allicin and diallyl sulfides that act as volatile toxins and repellents. Its essential oil extracts have been successfully formulated into nanoemulsions to improve delivery and persistence in pest management programs [14, 18]. These phytochemicals, although chemically diverse, share the ability to interfere with vital insect processes. Terpenoids and alkaloids disrupt nervous system signaling, flavonoids and tannins compromise digestive enzyme activity, and saponins enhance membrane permeability. Such multi-targeted action reduces the likelihood of resistance development, a significant drawback of conventional pesticides. For sericulture, these features make botanical agents especially suitable, provided that concentrations and application timing are carefully optimized [13, 14]. A comparative overview of major botanical sources, their active compounds, target pests, mode of action, and compatibility with silkworms is presented in Table 1.

Table 1: Botanical agents and their properties

Botanical source	Active compounds	Target pests	Mode of action	Silkworm compatibility	Reference
Neem (*Azadirachta indica*)	Azadirachtin, Salannin, Limonoids	Lepidopteran pests, leaf rollers, caterpillars	Hormonal disruption, feeding inhibition, reproduction interference	Sensitivity varies by larval stage; early instars highly sensitive	[1, 15]
Pongamia (*Pongamia pinnata*)	Karanjin, Pongamol, Phenolics, Flavonoids, Tannins	Caterpillars, sap-sucking pests	Feeding deterrent, antifeedant, growth inhibition	Encapsulation reduces acute toxicity; generally safe for later instars	[16, 17]
Garlic (*Allium sativum*)	Allicin, Diallyl sulfides	Aphids, caterpillars, whiteflies	Volatile toxin, repellent, growth disruption	Nanoemulsions improve safety; careful dosing required for young larvae	[14, 18]
Other Plant Oils (e.g., citronella, neem oil)	Terpenoids, Flavonoids, Alkaloids	Lepidopteran pests, aphids, whiteflies	Multi-target: nervous system, digestion, reproduction	Requires stage-specific dosing; generally lower residue persistence	[13, 14]

Experimental evidence from silkworm and pest trials

Laboratory and field trials provide valuable insights into the dual effectiveness and limitations of botanical pesticides. A recent study demonstrated that neem seed extract significantly affected the survival of silkworm larvae (*Bombyx mori*), with early instars being highly sensitive. Mortality in first instar larvae reached above 90% at higher concentrations, while biochemical assays revealed changes in detoxification enzyme activity, indicating that exposure induces metabolic stress in silkworms [1, 15].

Encapsulation technologies have been explored to improve the safety profile of botanicals. Pongamia oil microcapsules, for example, have been shown to deliver active compounds in a controlled manner, improving stability and prolonging activity against insect pests. Trials involving *Bombyx mori* larvae confirmed that encapsulated formulations exerted lower acute toxicity compared to crude extracts, while maintaining strong efficacy against pest insects in associated field settings [16, 17].

Garlic essential oil nanoemulsions have also been investigated for their role in pest control. While not always tested directly on silkworms, these formulations demonstrated high efficacy against Lepidopteran pests like Spodoptera littoralis, showing antifeedant activity, reduced larval weight gain, and disruption of pupal development. The broader implication is that such garlic-based products, once fine-tuned for dosage, can be integrated into sericulture systems without posing excessive risk to silkworm rearing [14, 18].

Formulation strategies and delivery systems

Recent innovations in botanical insecticide formulations have focused on enhancing stability, targeting, and controlled release to improve efficacy while reducing harmful effects on silkworms. Nanoinsecticides are a promising class, including nano-emulsions, nanocapsules, polymer-based nanoparticles, lipid-based formulations, and stimuli-responsive systems (e.g., responding to humidity, pH, light). These systems protect active compounds from rapid degradation (e.g., by UV, oxidation), improve adhesion to leaf surfaces, allow slow release, and enhance uptake by pest insects, thus reducing the dosage needed [19, 20].

Besides nanoformulations, oil-based and aqueous botanical formulations with adjuvants or surfactants have shown good field-level performance against Lepidoptera and sucking pests with acceptable safety margins. In one recent field study, oil-based and aqueous formulations of botanical extracts applied at appropriate concentrations achieved efficacy comparable to standard synthetic pesticides against pests like thrips, whiteflies, and red hairy caterpillars, while being less harmful to non-target organisms [21, 22].

These strategies, including choosing appropriate carriers, surfactants, optimizing droplet size, and using encapsulation or micro-capsules, help balance efficacy with safety, which is essential in silkworm rearing where leaf residue and larval sensitivity are major concerns. By minimizing pesticide residues on host plant leaves, such formulations reduce the likelihood of toxic ingestion by silkworms while maintaining effective pest suppression [19, 20].

Green formulations and delivery systems in botanical insecticides for sericulture

Advancements in botanical insecticide formulations have focused on enhancing efficacy, stability, and safety for silkworms through innovative delivery systems. These developments aim to improve the performance of plant-based pesticides while minimizing adverse effects on non-target organisms.

Nanoformulations in botanical insecticides

Nanoformulations, including nanoemulsions and nanoparticles, have emerged as effective delivery systems for botanical insecticides. These formulations enhance the solubility, stability, and bioavailability of active compounds, leading to improved pest control efficacy. For instance, nanoemulsions of plant oils have demonstrated increased insecticidal activity against various pests, including aphids and caterpillars, by facilitating better penetration and sustained release of active ingredients [23, 24]. Additionally, lipid-based nanoformulations have shown promise in encapsulating active compounds, protecting them from degradation and enhancing their efficacy against pests [25]. Such nano-delivery systems also allow precise targeting of pest tissues, reducing the overall dosage required and minimizing non-target effects on beneficial insects. Furthermore, these formulations can improve the environmental persistence of botanical compounds, maintaining bioactivity under field conditions without frequent reapplication [23, 24].

Biopolymer Carriers for Controlled Release

Biopolymer-based carriers, such as chitosan, alginate, and gum arabic, are utilized to encapsulate botanical insecticides, providing controlled release and protection of active compounds. These carriers offer advantages like biodegradability and reduced toxicity to non-target organisms. Studies have shown that biopolymer-encapsulated formulations of essential oils exhibit prolonged activity and enhanced stability under environmental conditions [26, 27]. Encapsulation also improves the compatibility of botanical insecticides with UV-sensitive compounds, preventing rapid degradation when exposed to sunlight. Furthermore, controlled-release biopolymer matrices can maintain effective pest suppression over extended periods, reducing the frequency of application and enhancing cost-efficiency. Moreover, the use of biopolymer carriers can facilitate the integration of botanical insecticides with microbial biopesticides, enhancing their efficacy and sustainability in pest management [28].

Essential Oil Emulsions for Enhanced Efficacy

Nanoemulsions of essential oils have demonstrated increased insecticidal activity against various pests, including aphids and caterpillars. This enhancement is attributed to the improved penetration and sustained release of active ingredients, which result in higher mortality rates and reduced LC50 values compared to conventional formulations. The encapsulation of essential oils in nanoemulsions provides controlled release, protecting the active compounds from rapid degradation due to environmental factors such as UV radiation and oxidation. This controlled release not only prolongs the efficacy of the insecticides but also minimizes the frequency of application, contributing to more sustainable pest management practices [21, 29].

Integration of Botanicals with Microbial Biopesticides

Combining botanical insecticides with microbial biopesticides offers a synergistic approach to pest management. This integration can enhance pest control efficacy, reduce the development of resistance, and promote sustainability in sericulture practices. Research indicates that the combination of plant-derived compounds with beneficial microorganisms can lead to improved pest suppression and ecological balance [28, 30]. These integrated formulations can also improve the persistence of active compounds in the environment, allowing for longer-lasting pest control without repeated applications [30]. Moreover, the use of compatible microbial strains alongside botanical extracts can stimulate natural pest predators and beneficial soil microbes, contributing to a more resilient agroecosystem [28]. Furthermore, such integrated approaches can reduce the reliance on chemical pesticides, contributing to more sustainable agricultural practices.

Safety, Regulatory, and Adoption Aspects

Effects on silkworm health

Botanical insecticides and other biopesticides are often promoted as lower-risk alternatives to synthetic pesticides, but they are not automatically safe for all non-target insects. Studies on silkworms (*Bombyx mori*) show that plant extracts and botanical formulations can cause dose- and stage-dependent toxic effects, including increased larval mortality, altered developmental timing, changes in enzymatic detoxification (esterases, glutathione S-transferases), and negative effects on gut microbiota that can reduce immunity and overall fitness. These physiological disruptions can translate into reduced larval growth and increased susceptibility to secondary infections, so safety testing must include multiple life stages and sublethal endpoints [1, 31]. Moreover, sublethal exposure to broad-spectrum insecticides such as λ-cyhalothrin has been shown to retard growth and cause higher abnormal pupation rates, even when survival appears unaffected in early larval stages [4]. Also, disturbances in gut microbiota induced by certain pesticide exposures, as seen with tolfenpyrad exposure, result in overgrowth of some bacterial genera and suppression of others, which may compromise digestion, immune signaling, and detoxification capacity in silkworms [2, 32].

Effects on silk yield and cocoon quality

Physiological stress during larval feeding, caused by toxic residues, antifeedants, or gut dysbiosis, can lower larval weight, interrupt silk gland development, and diminish cocoon weight and shell ratio. Experimental evidence shows that both lethal and sublethal exposures to botanical extracts or combinations with microbial toxins can impair silk yield parameters, especially when early instars are affected. Therefore, efficacy and safety evaluations of products intended for use around silkworms should include silk-production endpoints such as larval mass, cocoon weight, and shell ratio in addition to standard toxicological measures like mortality and behavioral changes [1, 4]. Recent trials also demonstrate that chronic sublethal exposures can disrupt silk-protein synthesis pathways, produce thinner or irregular filaments, and reduce cocoon quality [33, 34]. Moreover, pesticide-induced oxidative stress and autophagy in silk glands, triggered or exacerbated by certain agrochemicals, further weaken silk gland function and lower both cocoon quality and market value [35, 36]. The available experimental evidence on larval responses and impacts on cocoon and silk quality under different botanical formulations is summarized in Table 2.

Table 2: Safety Assessment of Botanical Pesticides on Silkworms

Botanical/ Formulation	Dose Tested	Larval Stage	Effects on Larvae	Impact on Cocoon/Silk Quality	Reference
Neem Seed Extract	High concentration (mg/L)	1st instar	>90% mortality; enzyme activity altered	Reduced cocoon weight, delayed pupation	[1, 15]
Pongamia Oil Microcapsules	Encapsulated, field dose	2nd–5th instar	Low acute toxicity; mild metabolic stress	Cocoon weight largely unaffected	[16, 17]
Garlic Essential Oil Nanoemulsion	0.5–1%	2nd–4th instar	Minor sublethal effects; reduced feeding in pests	Slight reduction in cocoon weight at higher doses	[14, 18]
λ-Cyhalothrin (comparison chemical)	Recommended field dose	1st–3rd instar	Retarded growth, abnormal pupation	Lower cocoon weight, impaired silk quality	[4]

Farmer adoption barriers (cost, availability, awareness, and perceived efficacy)

Adoption of botanical and biopesticide solutions by farmers is constrained by several interacting factors, such as higher per-unit cost versus off-the-shelf synthetics, limited availability/distribution chains, lack of timely local efficacy data, short shelf-life or variable product quality, and gaps in farmer awareness or trust. Socioeconomic studies show that farmers typically prioritize immediate and predictable pest control (fast knockdown and low cost). Where botanical/biological products underperform expectations or are perceived as unreliable, adoption stalls despite environmental advantages. Extension, demonstration plots, and subsidized access coupled with clear usage protocols are repeatedly recommended to overcome these barriers [37, 38]. Recent work further highlights that cultural preferences and traditional practices strongly shape farmer decisions, sometimes outweighing technical recommendations [39]. Additionally, policy incentives such as credit support or inclusion of biopesticides in official subsidy programs can significantly accelerate adoption [40].

Regulatory frameworks and gaps for botanical and microbial pesticides

Regulatory approaches for botanical and microbial pesticides vary by jurisdiction and often lag behind product innovation. Reviews of regulatory systems highlight three recurring issues: (1) inconsistent or unclear data requirements for registration of “natural” products, (2) test guidelines that were designed for chemical actives and do not always capture the unique biology of microbials or complex plant extracts, and (3) limited harmonization across regions which increases time and cost for market entry. Recent reviews emphasize that microbial pesticide assessment requires tailored infectivity/pathogenicity testing, environmental fate considerations (persistence, multiplication), and specific non-target organism testing protocols; similar bespoke guidance is needed for complex botanical mixtures where bioactive profiles and metabolites matter [41, 42, 43].

Practical implications and recommendations for silkworm rearing systems

To responsibly integrate botanicals and biopesticides into silkworm production systems, a set of pragmatic steps is needed. First, regulatory bodies should adopt tailored test guidelines for botanicals and microbials that include sublethal endpoints relevant to silk production (larval growth, gut microbiota, cocoon metrics) rather than relying solely on acute mortality tests [41, 42]. Second, product developers must provide validated use-instructions with explicit residue decay data and safe application windows relative to silkworm feeding; such data reduce uncertainty and protect cocoon quality [1, 4]. Third, adoption programs should combine subsidy or market-linkage incentives with extension demonstrations and locally generated efficacy data so farmers see reliable outcomes before switching away from cheap, fast-acting synthetics [37, 38].

Conclusion and Future Perspectives

Botanical pesticides and green formulations offer strong potential to reduce chemical risks in sericulture by providing effective pest suppression with lower persistence and generally reduced toxicity to silkworms compared with conventional pesticides [13, 44]. Advances such as nano-encapsulation, biopolymer carriers, and essential oil emulsions enhance stability and bioavailability, extending their field utility while reducing the need for repeated applications [45, 46]. However, limitations persist, including variability in extract composition, short residual activity, and insufficient data on long-term safety in silkworm rearing systems [4, 47]. Sublethal and physiological effects reported in some studies underscore the need for rigorous chronic toxicity assessments before large-scale deployment [1].

Future research should prioritize standardization of botanical formulations, comprehensive field trials that measure not only pest reduction but also cocoon quality and silk yield, and improved understanding of nanoformulation impacts on silkworm physiology [1, 46]. Policy and regulatory frameworks also need to evolve, with clearer guidelines for “low-risk” pesticides and supportive measures to enhance farmer adoption [28, 41]. If these gaps are addressed, green formulations can be integrated with biological control and cultural practices, positioning them as a cornerstone of sustainable sericulture.

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