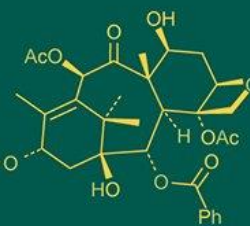
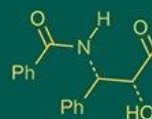


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Pesticide drift as an emerging threat to sustainable sericulture: Sources, impacts, detection, and mitigation strategies

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Abstract

Sericulture depends on an uninterrupted supply of uncontaminated mulberry foliage, yet mulberry gardens are frequently cultivated beside horticultural and field crops that receive intensive pesticide treatment. Off-target movement of these chemicals, commonly termed pesticide drift, is increasingly implicated in silkworm crop losses, but it remains a poorly quantified and largely unregulated hazard relative to its apparent scale. This review critically synthesises evidence on the sources, mechanisms, biological impacts, detection methods, and mitigation options for pesticide drift affecting mulberry-based sericulture. It examines spray, vapour, and particle drift and the agronomic and meteorological variables that govern them; the mulberry-adjacent cropping patterns that create exposure; documented effects on mulberry foliage and on *Bombyx mori*, including mortality, non-spinning syndrome, and sublethal effects on growth and silk yield; residue detection techniques ranging from chromatographic confirmation to portable biosensors; and farm-level, technological, and policy mitigation strategies. The review finds consistent evidence that neonicotinoid, diamide, and organophosphate residues carried by drift can impair silkworm survival and cocoon quality at concentrations far below levels of concern for the target crop, but finds almost no studies that directly quantify drift deposition onto mulberry foliage under field conditions, no validated residue thresholds specific to silkworm safety, and no standardised sampling protocols for sericulture landscapes.

Keywords: Pesticide drift, sericulture, mulberry, residue detection, drift mitigation

1. Introduction

Sericulture converts a single input, mulberry foliage, into cocoons through rearing process in which *Bombyx mori* larvae feed exclusively on leaf harvested from adjoining gardens. This dependence leaves almost no buffer between what happens agronomically in the surrounding landscape and what silkworms ultimately ingest: unlike livestock or aquaculture systems where feed can be sourced, tested, or substituted, mulberry leaf is typically cut and fed within hours of harvest, with no practical opportunity for decontamination.

Mulberry is rarely cultivated in isolation. In most sericulture regions it borders, or is interplanted with, horticultural and field crops such as rice, vegetables, cotton, sugarcane, and orchard fruit that receive comparatively intensive insecticide and fungicide programmes. As input intensity on these neighbouring crops has increased, so has the frequency with which spray applications move beyond their intended target, pesticide drift, through wind-carried droplets (spray drift), post-application volatilisation (vapour drift), windborne particles, or irrigation and runoff water.

Pesticide drift is not a new phenomenon, and its assessment and mitigation in general agriculture is well documented [1]. What distinguishes sericulture is the sensitivity of the exposed organism: *Bombyx mori* is a monophagous insect with a comparatively narrow detoxification gene repertoire relative to many polyphagous pest species [2], and can show acute or sublethal responses to residues that would be negligible for the crop on which they were applied. Reported consequences include larval mortality, non-spinning syndrome, and reduced cocoon weight and silk yield, drawn largely from leaf-dip bioassays and farmer surveys rather than from direct drift measurement in mulberry gardens.

Despite this accumulating toxicological evidence, pesticide drift is rarely treated as a distinct hazard category within sericulture research or extension practice. Sericulture pest-management guidance addresses pests and diseases of the mulberry plant and silkworm directly, while drift research addresses sensitive habitats, waterways, or bystanders, rarely mulberry gardens specifically. The mechanisms of drift are well characterised in general agronomy, and the toxicological sensitivity of *Bombyx mori* is well characterised in sericulture science, but the two fields have seldom been joined to ask how much drift actually reaches mulberry foliage under field conditions, and what would meaningfully reduce it.

This review addresses that gap. It synthesises evidence on the sources and mechanisms of pesticide drift, the cropping patterns that bring mulberry into contact with treated fields, the documented effects of drift-relevant pesticide classes on mulberry and on silkworm health, available residue detection technologies, and practical mitigation options at the farm, technology, and policy level. Rather than treating drift mechanisms and silkworm toxicology as separate subjects, the objective is to evaluate what is known, what is merely assumed, and what remains genuinely unresolved, so that future research and extension effort can be directed toward the questions that matter most for protecting sericulture from an increasingly crowded agricultural landscape.

2. Sources and Mechanisms of Pesticide Drift

Pesticide drift is generally classified into three physical forms. Spray drift is the off-target displacement of spray droplets during application, driven primarily by droplet size, wind speed, and release height. Vapour drift is the post-application movement of a chemical that volatilises from the treated surface and travels with air currents; it depends on the vapour pressure of the active ingredient and on temperature and relative humidity at and after application, and can carry residues over much greater distances than spray drift, sometimes kilometres under temperature-inversion conditions [1]. Particle drift refers to windborne movement of dust or soil particles carrying adsorbed residues, and is a secondary but locally important pathway in dry, tilled landscapes. A further, indirect route is contamination through irrigation water or surface runoff carrying dissolved or particle-bound residues from a treated field into an adjoining mulberry garden, though this pathway is far less studied than airborne drift.

Across these forms, droplet size is the factor most consistently identified as governing drift potential: fine droplets are disproportionately prone to wind displacement, while coarser droplets settle closer to the application zone [1]. Nozzle type and spray pressure jointly determine the droplet spectrum, and low-pressure, drift-reducing nozzles that shift the distribution toward coarser droplets are consistently reported to cut particle drift without necessarily lowering pest-control efficacy [3]. Wind speed and direction determine how far droplets travel and toward which neighbouring field; most guidance recommends suspending application above moderate wind speeds and avoiding calm, temperature-inversion conditions that trap vapour near the ground. Air-assisted sprayers can reduce drift in orchard and vineyard settings compared with conventional application, though the benefit depends on correct air-volume and airflow settings.

Aerial application, whether by fixed-wing aircraft or increasingly by unmanned aerial vehicles (UAVs), introduces a drift pathway of direct relevance to mixed mulberry landscapes, since drones are now widely used for rice and field-crop spraying in parts of Asia where mulberry is also grown. Field monitoring of UAV-sprayed rice paddies found that pesticide residue on non-target crops fell as buffer distance increased, and fell further where a windbreak crop such as maize separated sprayed and non-target fields, with reductions of up to 100 percent at the greatest buffer distances tested [4], one of the few studies to directly quantify drift deposition on neighbouring vegetation under working farm rather than wind-tunnel conditions, broadly consistent with older, non-drone-based drift research [5, 6].

A recurring limitation, general rather than sericulture-specific, is that most drift-factor measurements rely on inert collectors, glass slides, filter paper, or water-sensitive cards, rather than on the foliage of a living non-target crop being fed to an animal. How closely collector-based drift measurements approximate actual residue loads on mulberry leaf, and how that load translates into a dose ingested by a feeding silkworm, has essentially not been examined directly.

3. Pesticide Drift in Mulberry-Based Cropping Systems

Mulberry is grown as a monoculture in a minority of sericulture landscapes. More typically, mulberry gardens border, rotate with, or are interplanted alongside horticultural and field crops within the same watershed or even the same farm, a pattern documented repeatedly in Indian sericulture districts where farmers cultivate mulberry alongside vegetables, cotton, sugarcane, rice, or fruit orchards depending on local market conditions and land availability [7]. This adjacency is agronomically convenient, since mulberry is a perennial hedge or block crop that can be fitted around annual rotations, but it places mulberry gardens directly downwind, or down-slope, of crops that typically receive far more intensive pesticide input than mulberry itself, which is grown primarily for leaf quality rather than as a target of heavy chemical control. A leaf-dip dosing study screening of chlorantraniliprole, flubendiamide, and imidacloprid specifically for their effect on mulberry silkworm rearing performance illustrates how directly these neighbouring-crop compounds translate into sericulture outcomes once they reach the leaf [8].

The pesticide groups most frequently implicated in drift-related silkworm losses reflect what is sprayed on neighbouring crops rather than any inherent affinity for mulberry. Neonicotinoids, used extensively on rice, vegetables, and cotton against sucking pests, together with fipronil account for a substantial share of the global insecticide market [9], in Chinese regions where mulberry orchards adjoin rice and citrus, drift of the neonicotinoid nitenpyram applied against planthoppers and aphids poses an unacceptable risk to silkworms at mulberry-field peripheries under a formal risk-quotient assessment [10]. Anthranilic diamides such as chlorantraniliprole and flubendiamide, widely used on rice, sugarcane, and vegetables, are similarly implicated: a survey across mulberry-growing districts of Karnataka, India found that of 120 sericulture farmers, 66 attributed silkworm crop damage to pesticide air-drift and 38 to direct contact, with chlorantraniliprole, flubendiamide, imidacloprid, dichlorvos,

carbaryl, dimethoate, and chlorpyrifos identified in and around mulberry fields ^[7]. Organophosphates such as chlorpyrifos and dichlorvos remain in use on neighbouring crops and continue to appear in silkworm poisoning reports ^[11]. Fungicides are a comparatively under-examined drift hazard, though residue exposure affects silkworm cocooning at non-lethal doses ^[12].

The exposure pathway from field to feeding tray is short and largely unbuffered: pesticide applied to an adjoining crop

can settle on mulberry foliage as spray or vapour drift, accumulate in surface soil and be redeposited onto lower leaves, or reach the garden through irrigation channels; leaf is then harvested, chopped, and fed to larvae within the same day, leaving little time for residue dissipation. A separate soil-residue survey around mulberry gardens reported contamination patterns consistent with this route ^[13].

Table 1: Major horticultural crops adjacent to mulberry and commonly used pesticide groups

Neighbouring Crop	Common Pesticide Groups	Relevance to Sericulture Drift Risk
Rice	Neonicotinoids, organophosphates	Frequently adjoins mulberry in China/India; nitenpyram drift risk formally quantified ^[10]
Vegetables (cotton, tomato, ginger)	Diamides, pyrethroids, organophosphates	Air-drift repeatedly implicated in farmer-reported silkworm loss ^[7]
Cotton	Pyrethroids, neonicotinoids, organophosphates	Common rotation/adjacency crop across Indian sericulture belts ^[7]
Sugarcane	Anthranilic diamides	Air-drift linked to silkworm mortality at very low leaf concentrations ^[14]
Citrus/orchard fruit	Neonicotinoids, fungicides	Adjoins mulberry in Chinese regions; mist drift documented ^[10]
Fungicide-treated horticultural crops	Triazoles (tebuconazole)	Under-examined hazard; sublethal cocooning effects at non-lethal levels ^[12]

4. Effects of Pesticide Drift

4.1 Effects on Mulberry

Evidence on the direct physiological effects of drift-level pesticide exposure on the mulberry plant itself is comparatively sparse relative to the evidence base on silkworm toxicology. Where herbicide or insecticide drift reaches mulberry foliage at sufficient concentration, visible leaf injury, chlorosis, necrotic spotting, or leaf curling has been described in sericulture field observations, though controlled, dose-response studies of mulberry leaf injury from drift-relevant concentrations remain largely absent from the peer-reviewed record. Residue accumulation on and within mulberry leaf tissue is better documented indirectly, through the repeated finding that field-collected mulberry leaf and soil samples test positive for pesticide residues using both survey-based and biosensor-based screening methods ^[14], confirming that contamination occurs even where its physiological consequence for the plant has not been separately quantified.

The nutritional quality of mulberry leaf, its protein, moisture, and mineral content, is the trait most directly relevant to silkworm performance, since larvae raised on leaf of poor nutritional quality show reduced growth and silk output independent of any direct pesticide toxicity. Whether sub-visible pesticide exposure measurably alters mulberry leaf nutritional composition, as distinct from contaminating its surface with residue subsequently ingested by the silkworm, remains essentially unaddressed at present. This represents an important gap: current understanding treats mulberry primarily as a passive residue carrier rather than as a plant whose own physiological stress response to sub-lethal chemical exposure might independently affect leaf quality and, in turn, silkworm nutrition.

4.2 Effects on Silkworms

Toxicological evidence on *Bombyx mori* and pesticide exposure is considerably more developed than the corresponding plant-side evidence, and provides the strongest indication that drift-transported residues threaten sericulture. Acute exposure of silkworm larvae to field-relevant concentrations, delivered by leaf-dip bioassay to

simulate residue contact, produces a consistent symptom complex: vomiting of gut fluid, body flaccidity, rectal protrusion, chain-like faeces, body shrinkage, and, at higher concentrations, mortality ^[14]. Susceptibility varies by chemical class and developmental stage rather than uniformly: in one screening study, flubendiamide and a buprofezin-fipronil combination produced complete non-spinning at low concentrations, while chlorantraniliprole and imidacloprid did not, indicating no single potency ranking applies uniformly across chemical classes ^[14].

4.3 Non-spinning syndrome

A distinctive and repeatedly documented sublethal outcome of pesticide toxicity in silkworms is non-spinning syndrome, in which larvae exposed to insect growth regulators, diamides, or other developmentally disruptive compounds at very low, sub-lethal doses fail to pupate or spin a cocoon within the normal period. Affected larvae typically continue feeding and growing to a near-mature size but do not initiate spinning behaviour; they persist for several days beyond the normal mounting stage before becoming sluggish, discoloured, and eventually dying without producing a cocoon ^[14]. Flubendiamide and buprofezin-fipronil combination have been shown to induce complete non-spinning at low residue concentrations, while other classes, including several organophosphates and certain neonicotinoids, produce non-spinning at a lower frequency alongside acute mortality, indicating that the syndrome is not confined to a single mode of action but reflects a broader disruption of the hormonal and developmental signalling that triggers cocoon formation ^[14, 16]. Because non-spinning syndrome causes complete loss of the cocoon crop without necessarily causing early larval death, it is arguably the most economically damaging outcome of drift-level pesticide exposure, and it may be under-recorded relative to acute mortality in farmer-reported losses, since a rearer observing surviving but non-spinning larvae may not immediately attribute the loss to pesticide exposure rather than to disease or poor-quality feed.

Neonicotinoids have received particular research attention because of their systemic mode of action and widespread

use on crops adjoining mulberry. Nitenpyram, applied to rice and other field crops against planthoppers and aphids, causes oxidative stress, DNA damage, and altered microRNA expression linked to metabolic and immune signalling in exposed silkworms, at concentrations consistent with drift onto adjoining mulberry foliage (10). Sublethal neonicotinoid exposure more broadly prolongs larval development and reduces body weight, pupation rate, and cocoon-related economic traits even where mortality is not observed, meaning non-lethal drift exposure can still reduce silk yield [15]. Comparable sublethal effects on cocoon formation follow low-dose fungicide (tebuconazole) exposure and exposure to insect growth regulators such as novaluron, which impairs silk gland structure and productive performance even at non-lethal levels [12, 16]. These sublethal effects are consistent with molecular evidence that detoxification-enzyme systems in the silkworm midgut and fat body are measurably activated by low, drift-relevant doses of acetamiprid and chlorantraniliprole respectively, indicating a physiological cost to sublethal exposure even where no visible symptom is

produced [17, 18]. Pesticide exposure may also compound disease susceptibility rather than acting independently of it: sublethal phoxim exposure has been shown to interact with *Bombyx mori* nucleopolyhedrovirus infection to elevate silkworm mortality beyond either stressor alone, suggesting that drift exposure could worsen outcomes from unrelated pathogens circulating in a rearing house [19].

Taken together, this evidence indicates that the threat drift poses to sericulture is not confined to acute mortality events large enough to be immediately obvious to a rearer. Sublethal effects on growth, pupation, and cocoon quality are well documented across several pesticide classes and appear capable of eroding silk yield even where the pesticide concentration reaching the mulberry garden falls well short of an acutely lethal dose. This distinction matters directly for the detection and mitigation strategies discussed in the following sections, since a monitoring approach calibrated only to detect concentrations associated with visible mortality would miss the sublethal exposure levels now shown to affect cocoon economics.

Table 2: Reported effects of different pesticide classes on mulberry and *Bombyx mori*

Pesticide Class	Example Compounds	Reported Effects
Neonicotinoids	Nitenpyram, imidacloprid, acetamiprid	Oxidative stress, DNA damage, altered miRNA expression, reduced pupation and cocoon weight, midgut detoxification-enzyme induction
Anthranilic diamides	Chlorantraniliprole, flubendiamide	High acute mortality and non-spinning at low leaf concentrations; fat-body detoxification-enzyme induction
Organophosphates	Chlorpyrifos, dichlorvos, phoxim	Genotoxicity, acetylcholinesterase inhibition; interacts with viral infection to raise mortality
Insect growth regulators	Novaluron, buprofezin	Non-spinning syndrome; impaired silk gland structure and productive performance
Fungicides	Tebuconazole	Sublethal effects on cocooning at non-lethal residue exposure
Pyrethroids/mixed formulations	Bifenthrin, buprofezin-fipronil	High mortality and non-spinning in leaf-dip screening bioassays

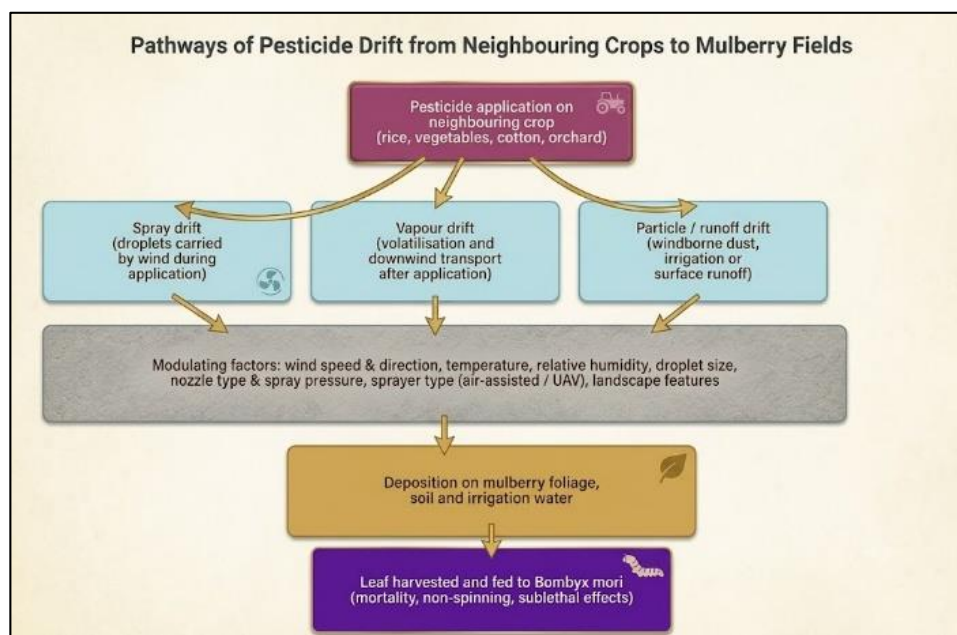


Fig 1: Pathways of pesticide drift from neighbouring crops to mulberry fields

5. Detection and Monitoring

Confirmatory quantification of pesticide residues on mulberry leaf or soil relies on the same infrastructure used across agricultural residue testing generally: gas chromatography-mass spectrometry (GC-MS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS), typically preceded by the QuEChERS (quick, easy, cheap,

effective, rugged, safe) extraction method, using acetonitrile extraction and dispersive solid-phase clean-up to prepare plant material for multi-residue analysis [20]. These methods offer the sensitivity and specificity to confirm which active ingredients are present and at what concentration, and remain the reference standard against which faster methods are judged. Their limitation for sericulture is practical: GC-

MS and LC-MS/MS require laboratory infrastructure and a turnaround measured in days, a poor match for a rearing cycle in which leaf is fed within hours of harvest and a delayed result cannot prevent the exposure it detects.

This mismatch has driven interest in faster, field-deployable screening, most relying on some form of biosensor rather than chromatographic separation. Enzyme-inhibition biosensors, most commonly based on acetylcholinesterase (AChE), a well-established exposure biomarker in environmental and occupational toxicology [21], exploit the same mechanism through which organophosphate and carbamate pesticides act on the insect nervous system: exposure inhibits AChE activity, read out colorimetrically or electrochemically as a proxy for contamination without identifying the specific compound [23]. Transcriptional induction of acetylcholinesterase genes has itself been documented in *Bombyx mori* following organophosphate exposure, supporting AChE as a biomarker in this species specifically [22].

A paper-strip AChE assay developed specifically for sericulture use, with enzyme and substrate dried onto filter paper and exposed to a mulberry-leaf or soil extract, has been validated against farmer-collected field samples from several Indian states, correctly distinguishing pesticide-positive from negative samples by colour-change readout

alone, at a cost and turnaround realistically usable before feeding a batch of leaf [14]. Because AChE inhibition is also produced by non-organophosphate classes at sufficiently high concentration, such assays function as a general contamination screen rather than a compound-specific tool, acceptable for a go/no-go feeding decision but not a substitute for confirmatory laboratory analysis [14].

Beyond enzyme-inhibition platforms, broader biosensor research includes immunoassay-, aptamer-, and nanomaterial-based electrochemical and optical sensors developed for pesticide residue screening in food and agricultural produce generally, several of which report detection limits in the low nanogram-per-millilitre range under laboratory conditions [23]. None of these platforms have been validated specifically against mulberry leaf matrices or against the residue concentrations shown to affect silkworm health, which limits confidence in transferring reported laboratory sensitivity directly to a sericulture field-screening context. A rapid, low-cost paper-strip format, rather than a laboratory-grade instrument, is the format most consistent with the resource constraints and time pressure of an actual rearing operation, and is the direction in which sericulture-specific detection research to date has moved [14, 24].

Table 3: Detection techniques for pesticide residues: principles, advantages, limitations, and suitability for sericulture

Technique	Principle	Advantages/Limitations	Suitability for Sericulture
GC-MS	Chromatographic separation with mass-spectrometric detection	High sensitivity and specificity; laboratory-bound, slow turnaround, costly	Reference confirmatory method; unsuitable for pre-feeding, same-day screening
LC-MS/MS	Chromatographic separation with tandem mass-spectrometric detection	Handles polar and thermolabile compounds; same infrastructure demands as GC-MS	Same as GC-MS; used for confirmatory multi-residue surveys
QuEChERS extraction	Acetonitrile extraction with dispersive solid-phase clean-up	Simple, low-cost sample preparation; still requires instrumental analysis afterward	Useful as a preparatory step before GC/LC-MS, not a standalone field method
Enzyme-inhibition biosensor (AChE)	Colorimetric or electrochemical readout of enzyme inhibition	Fast, low-cost, field-usable; not compound-specific, can give false positives	Validated directly on mulberry leaf and soil extracts in one field study
Paper-strip rapid test	Dried reagents on filter paper with visual colour-change readout	Very low cost, no instrumentation, farmer-operable; semi-quantitative only	Best match identified for pre-feeding go/no-go screening

6. Mitigation Strategies

6.1 Farm-level strategies

Physical separation between sprayed fields and mulberry gardens, commonly formalised as an unsprayed buffer strip, is among the most extensively evaluated drift-mitigation measures in general agriculture, with buffer width shown to reduce off-target deposition onto adjoining ditches, waterways, and non-target vegetation as distance from the sprayed field increases [6], consistent with drone-sprayed rice paddy monitoring finding residue on non-target crops falling by up to 100 percent as buffer distance increased, and further where a windbreak crop such as maize separated sprayed and non-target fields [4]. Windbreaks have an independent evidence base showing drift reductions of 60 to 90 percent under favourable conditions, though porosity, height, and placement all affect performance and no standardised design method exists [5]. Neither measure has been evaluated specifically around mulberry gardens; their sericulture effectiveness is inferred from general agricultural drift research rather than demonstrated directly.

Spray scheduling and communication between neighbouring farmers about planned spray dates are low-cost measures repeatedly recommended in drift-management guidance, though effectiveness depends on voluntary compliance and

is difficult to verify. Integrated Pest Management on the neighbouring crop addresses drift risk indirectly by reducing total spray events, but adoption on crops adjoining mulberry is not something sericulture extension programmes typically influence, since the neighbouring farmer, not the sericulturist, makes that decision.

6.2 Technological approaches

Drift-reducing nozzles that shift droplet size toward coarser droplets, and precision or air-assisted sprayers that direct spray more accurately into the canopy, both reduce off-target drift without necessarily reducing pest-control efficacy, though effects on non-target beneficial arthropods vary with technique [3]. Weather-based spray advisory systems, restricting application windows to periods of acceptably low wind and stable conditions, could in principle be extended to flag drift risk toward known mulberry-garden locations, though no sericulture-specific implementation was identified. Drone application is double-edged for sericulture landscapes: UAV spraying is increasingly used on crops bordering mulberry, and while it introduces a further drift source, drone-specific studies have generated some of the only field-quantified buffer and windbreak-effectiveness data available for any drift-

mitigation measure, data that could plausibly be adapted into UAV guidelines for use near mulberry gardens ^[4].

6.3 Policy recommendations

Good Agricultural Practice guidance, farmer awareness programmes, and extension support are frequently proposed as the mechanism through which the farm-level and technological measures above would actually reach practice,

but no evaluation of whether such programmes have been implemented, still less evaluated for effectiveness, specifically to protect mulberry plantations from neighbouring-crop drift could be identified. Regulatory measures such as mandatory buffer zones exist in some jurisdictions for other sensitive land uses, such as waterways and apiaries, but an equivalent regulatory category for mulberry gardens has yet to be established.

Table 4: Mitigation strategies, expected effectiveness, implementation challenges, and research needs

Strategy	Expected Effectiveness	Implementation Challenges	Research Needs
Buffer zones	Drift declines with distance; well demonstrated generally	Requires land allocation; not mandated around mulberry	Mulberry-specific buffer-distance studies
Windbreaks	60-90% drift reduction under favourable conditions	No standardised design/porosity guidance	Field trials around mulberry gardens
Drift-reducing nozzles/precision sprayers	Reduce drift without loss of target efficacy	Requires neighbouring-farmer adoption	Verification near mulberry-adjacent fields
Spray scheduling/farmer communication	Plausible benefit; low cost	Voluntary; hard to verify	Formal extension protocols
UAV operating guidelines	Buffer/windbreak effects quantified for drone spray	Not yet sericulture-specific	Adapt UAV buffer data to mulberry contexts
GAP/farmer awareness/extension	Scales all other measures	No evaluated programme identified	Pilot and evaluate extension interventions
Portable residue sensors	Enables go/no-go decision before feeding	Semi-quantitative; limited validation	Multi-class quantitative sensors on mulberry matrices

7. Research Gaps

7.1 Lack of studies directly quantifying drift into mulberry fields: Aside from drone studies around rice paddies, where mulberry was not the monitored crop ^[4], no study measured pesticide deposition directly onto mulberry foliage under field conditions using a quantitative collection method; evidence is drawn almost entirely from symptom surveys and after-the-fact residue samples ^[7, 14].

7.2 Insufficient residue threshold values for silkworm safety: Toxicological studies establish LC50 values under controlled leaf-dip conditions ^[25], but no framework currently translates these into a field-usable maximum residue threshold specific to silkworm safety.

7.3 Limited long-term field monitoring: Cited toxicology derives from single-batch, short-duration bioassays; no study followed drift exposure and its cocoon-yield consequences across a full rearing season or successive seasons.

7.4 Lack of standardised sampling protocols: Studies sampling mulberry leaf or soil use varying collection methods and reporting units, preventing direct comparison across regions.

7.5 Poor understanding of chronic, low-dose exposure: Sublethal effects are documented for single, defined exposure events ^[12, 15, 16], but repeated low-level exposure across a rearing cycle, arguably more realistic, has been little studied.

7.6 Limited economic assessment of drift-related losses: No study placed a monetary value on cocoon crop loss attributable specifically to drift, as distinct from pesticide exposure generally.

7.7 Few predictive models tailored to sericulture landscapes: Weather-and GIS-based drift prediction tools exist for general agriculture, but none incorporate mulberry

garden locations as a protected category.

8. Future Perspectives

Several directions follow directly from the gaps identified above and are grounded in technologies already demonstrated, if not yet applied, in a sericulture context. Precision spraying technologies, drift-reducing nozzles, air-assisted and precision sprayers, and calibrated UAV application, have demonstrated drift reductions in general agriculture and orchard settings ^[3, 4] and could be incorporated into extension guidance for farmers cultivating crops adjacent to mulberry, even though sericulture programmes cannot mandate their neighbours' equipment choices.

GIS and weather-based drift risk prediction, layering known mulberry garden locations onto existing wind, humidity, and temperature-inversion forecasting already used for spray-timing advisories, would extend an existing capability to a new protected-area category rather than requiring new infrastructure. Portable residue sensors, building on the paper-strip AChE platform already validated for sericulture use ^[14], are the most immediately deployable detection technology, and further development toward multi-class or semi-quantitative readouts would improve their utility for go/no-go feeding decisions.

Landscape-level planning, formally designating buffer distances or windbreak requirements around registered mulberry plantations, would translate general drift-mitigation evidence ^[5, 6] into a sericulture-specific protective category, analogous to existing buffer provisions for waterways or apiaries. Integrating pesticide stewardship into sericulture extension programmes, so drift-risk awareness reaches rearers through channels already used for pest and disease advisory, would address the extension gap without a new institutional structure. None of these directions requires unproven technology; each depends on extending existing tools to include mulberry gardens as a protected land use, and on generating the field data that would justify that extension.

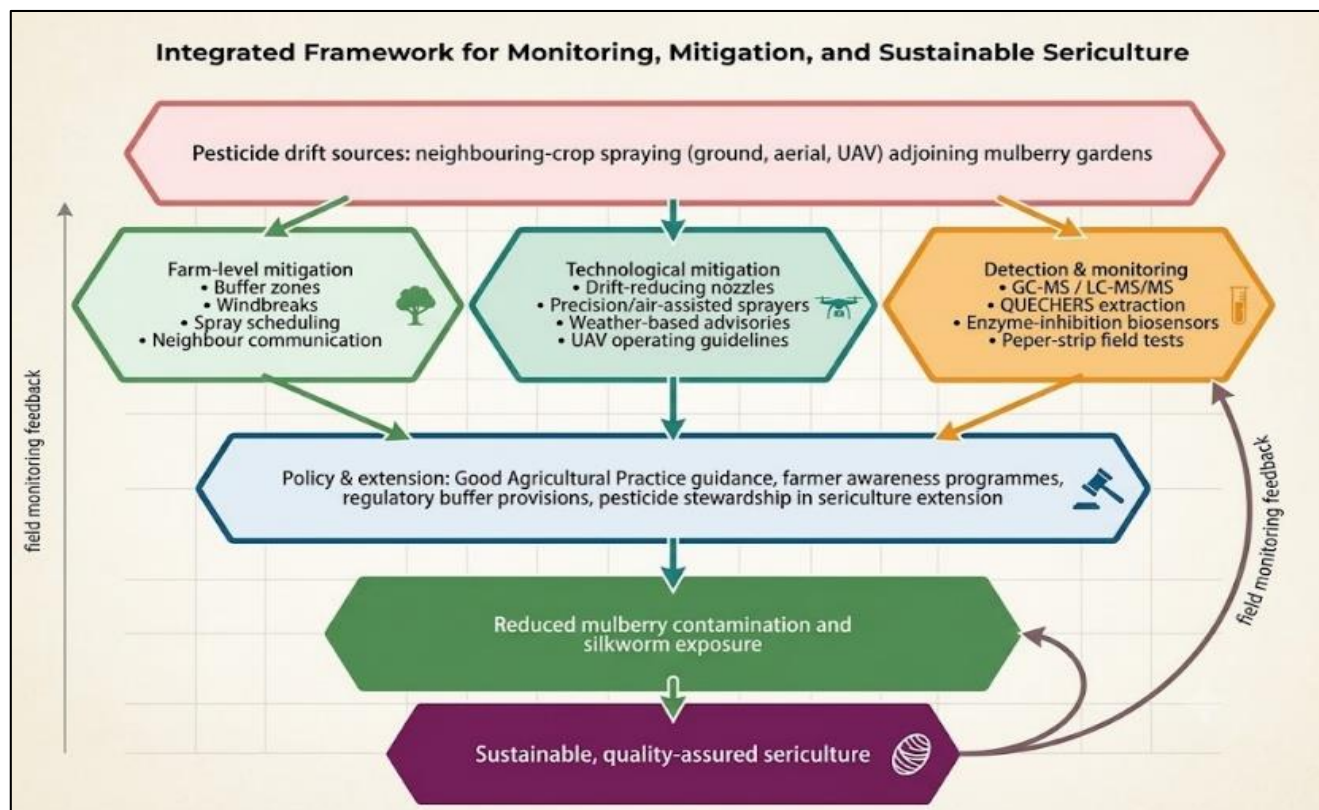


Fig 2 Integrated framework for monitoring, mitigation, and sustainable sericulture

9. Conclusion

Pesticide drift from crops adjoining mulberry gardens is supported by a substantial body of toxicological evidence showing that *Bombyx mori* can suffer mortality, non-spinning syndrome, and reduced growth, pupation, and cocoon quality following exposure to neonicotinoid, diamide, organophosphate, and fungicide residues, several of which have been traced specifically to drift from neighbouring fields rather than to direct application on mulberry itself. Detection technology has progressed from laboratory-confined chromatographic confirmation toward field-deployable enzyme-inhibition biosensors that a rearer can plausibly use before a feeding decision, and mitigation options, buffer zones, windbreaks, drift-reducing spray technology, and weather-based application timing, are well established in general agriculture even though they have rarely been evaluated around mulberry specifically.

The central limitation of current knowledge is not toxicological but empirical. Almost every available study either measures silkworm response to a controlled, single-event exposure in the laboratory or documents farmer-reported symptoms after the fact; almost none directly measures how much pesticide actually reaches mulberry foliage during a real neighbouring spray event, over what distance, or under what conditions existing mitigation measures would meaningfully reduce that exposure in a sericulture landscape specifically. Closing this gap does not require new toxicological science; it requires field deposition studies, standardised sampling protocols, and silkworm-specific residue thresholds applied to the mulberry-adjacent cropping systems where most sericulture actually takes place.

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