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Digital and climate-smart extension strategies for sustainable sericulture

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Abstract
Sericulture is a unique farm-based industry that connects smallholders to global textile markets. It provides income and employment, but its success depends on effective extension systems. Farmers need timely guidance on mulberry cultivation, silkworm rearing, and pest and disease management. Traditional face-to-face extension often struggles to reach dispersed communities and address climate challenges. Digital tools and climate-smart approaches are helping overcome these gaps. Mobile applications, messaging platforms, and decision-support systems improve the speed and reach of technical advisories. Participatory models, such as farmer field schools, build trust and encourage adoption. Climate-smart strategies, including resilient mulberry varieties, adaptive rearing practices, and pest forecasting, support farmers in managing climate risks. Integrated approaches that combine digital delivery with practical climate-smart content, backed by policy and institutional support, offer the best pathway for sustainable extension. Future efforts should focus on localised decision-support systems, participatory climate services, and innovative monitoring tools to strengthen resilience in sericulture.

Keywords: Sericulture extension, climate-smart practices, decision-support systems, rural livelihoods, technology adoption

1. Introduction

Sericulture plays an important role in rural economies by providing supplementary income, employment opportunities, and a pathway for value addition in silk-based products. Its strength lies in being a land-based activity that can be integrated with smallholder farming systems, particularly in regions with limited industrial employment [1]. Because of this, sericulture has been repeatedly highlighted as a livelihood support option with social and economic benefits for rural households [2].

Sustaining productivity in sericulture depends heavily on knowledge transfer and technical guidance. Mulberry leaf quality, silkworm health, pest and disease management, and hygienic rearing practices all require precise and timely information. This makes extension systems essential for maintaining crop stability and farmer income [3]. Conventional extension models, however, face challenges in reaching widely dispersed producers, which slows the adoption of improved varieties, climate-resilient technologies, and better post-cocoon practices [4].

In recent years, climate variability has emerged as a critical factor influencing sericulture. Heat stress, irregular rainfall, and changes in pest dynamics have been shown to affect mulberry physiology and silkworm development, leading to unstable cocoon yields [5, 6]. Extension strategies therefore need to incorporate climate-smart advisories that build resilience into sericulture systems [7].

Digital tools are increasingly recognized as a practical means of addressing these challenges. Mobile applications, messaging platforms, and decision-support systems have demonstrated potential to deliver timely information, diagnostic support, and localized weather advisories [8, 9]. When designed in collaboration with farmers, these tools complement traditional extension by reducing delays, lowering transaction costs, and making advisory services more responsive [4].

Integrating digital delivery with climate-smart content creates an effective extension pathway for sericulture. Such models can combine real-time weather alerts with recommendations on host plant care, rearing practices, and pest management, while also supporting peer learning among farmer groups. These approaches hold promise for strengthening resilience, improving productivity, and making advisory systems more accessible to diverse groups of sericulture farmers.

2. Current Challenges in Sericulture Extension

Sericulture is knowledge-intensive. Good cocoon yields and silk quality depend on precise timing, clean rearing, proper mulberry nutrition, and rapid responses to pests and diseases. That technical intensity increases the value of extension services, but it also raises the cost of delivering useful advice. Traditional, face-to-face extension systems struggle to reach widely dispersed smallholders, especially in hill and tribal areas where many sericulturists live. Weak extension coverage limits regular monitoring, on-farm demonstrations, and the rapid troubleshooting that rearing cycles demand [10, 11].

Many empirical adoption studies show a mixed picture. Some farmers adopt a high share of recommended technologies (for example, bivoltine rearing in pockets), while many others show only partial or slow uptake of improved practices. Socioeconomic factors such as education, contact with extension agents, membership of farmer groups, and access to credit strongly affect adoption. When extension contacts are infrequent or generic, uptake of more demanding practices, for example- controlled rearing environments, improved strains, or post-cocoon mechanisation) remains low [10, 12]. These adoption gaps reveal that simply producing technology packages is not enough; delivery must match local capacity and incentives.

Climate variability is magnifying the problem. Mulberry leaf quality and silkworm physiology are tightly linked to microclimate. Rising temperatures, erratic rainfall, and humidity spikes change leaf phenology and increase pest/disease pressure, which in turn shorten optimal rearing windows and raise mortality risk. Extension systems must therefore provide timely, location-specific climate-smart advice such as altered rearing calendars, shade and irrigation measures, and pest forecasting. Recent reviews and field studies report that sericulture losses are increasingly tied to climate shocks, making reactive extension insufficient and underscoring the need for anticipatory advisories [3, 13].

Technology dissemination suffers from classic "last-mile" problems. New tools (improved mulberry cultivars, low-cost dryers, mechanised reeling, decision-support tools) often exist, but distribution channels, training modules, local demonstration units and spare-parts supply are weak. In parallel, digital extension tools (WhatsApp, SMS, apps) show promise for scaling advisory reach, but poor infrastructure, limited digital literacy, language barriers, and low trust reduce effectiveness unless tools are co-designed with users and integrated with local extension agents [8, 9, 14]. In short, technology supply is often ahead of the institutional capacity to deliver it in usable form.

Finally, institutional and economic constraints matter. Smallholders face liquidity shortages, high labour costs during peak rearing months, and weak market linkages for quality cocoons. Extension programs that ignore these structural constraints for example, by recommending equipment that requires capital outlay without linking to credit or collective purchase options see poor uptake. Evidence suggests integrated delivery (technical, finance and market information) and participatory extension models raise adoption and resilience more effectively than supply-driven campaigns alone [8, 12].

The current challenges are threefold and interlinked: (1) limited and uneven extension reach with often generic advisories; (2) pressure from climate variability that demands rapid, location-specific recommendations; and (3) persistent gaps in converting available technologies into on-farm practice because of infrastructure, literacy, institutional and economic barriers. Any effective modern extension model for sericulture will need to address all three dimensions simultaneously [8, 13, 14].

3. Digital Tools, and Information and Communication Technology (ICT) Based Extension in Sericulture

Sericulture is particularly well suited to digital extension because rearing and mulberry management demand frequent, time-sensitive actions. Digital channels can deliver concise, actionable messages such as rearing schedules, hygiene checks, and pest alerts, richer media like how-to videos, and near-real-time diagnostics that traditional face-to-face extension cannot provide at scale [4, 8]. These tools are not a substitute for field staff; they amplify human facilitators and extend their reach. When digital platforms are co-designed with local advisers and farmer groups, and integrated into existing extension routines, they increase the speed and relevance of advice while maintaining local contextualisation [4, 9].

3.1 Mobile Applications, Messaging Platforms, and E-Portals

Mobile applications, messaging platforms (notably WhatsApp) and e-portals are now central channels for delivering time-sensitive sericulture advice. These channels can push cocoon-harvest schedules, mulberry fertilizer/ irrigation reminders, pest alerts and market prices directly to farmers' phones, enabling near-real-time decisions that match the tight timing requirements of silkworm rearing [8, 15]. Peer-learning via WhatsApp groups is especially important: moderated farmer groups let members post photos of leaf symptoms or larval behaviour, get quick feedback from extension agents or lead farmers, and archive practical Q&A for later reference. Empirical content-analyses and field studies from India show WhatsApp groups support knowledge exchange and build virtual communities of practice, which in turn improves farmers' diagnostic confidence and shortens the time to corrective action [8, 16].

For sericulture specifically, researchers have begun documenting mobile tools that directly address rearing tasks. For example, an Indian research team developed a disinfection-card and mobile app (SeriApp) to help farmers calculate disinfectant doses and schedule rearing-house sanitation. This simple, targeted tool addresses a high-impact rearing practice and shows how small, well-focused apps can raise compliance with hygiene protocols [17]. Adoption studies also show that socio-economic factors, such as education, extension contact, and phone access strongly shape who benefits from mobile advisory services, so localization (language), low-bandwidth formats and moderation by trusted actors are key design requirements [8, 15]. To consolidate these examples, Table 1 summarizes key digital tools currently applied in sericulture extension and highlights their core functions.

Table 1: Digital tools for sericulture extension and their functions

Tool	Functions	Reference
Mobile apps & messaging (WhatsApp, SeriApp, Telegram groups)	Pest/disease alerts, rearing schedules, disinfection calculators, farmer-to-farmer sharing, photo-based problem reporting	[16, 17]
E-portals & SMS services	Market prices, weather alerts, training modules, advisory bulletins	[8, 15]
Decision Support Systems (DSS)	Forecasting disease/pest risks, weather-linked rearing advice, mulberry crop health recommendations	[18, 19]
Remote diagnostics (AI/computer vision, IoT sensors)	Automated silkworm disease detection, mulberry pest monitoring, real-time farm data collection	[19, 20]

3.2 Decision-Support Systems and Remote Diagnostics

Decision-Support Systems (DSS) and remote diagnostics move digital extension beyond one-way advisories to context-aware, data-driven recommendations. Modern DSS combine weather predictions, pest risk models, and crop-stage schedules to generate customised suggestions. For sericulture, this includes the best times to start rearing, advise on ventilation and shade, and alarm windows for potential disease outbreaks [18]. Several studies in agri-ICT show DSS can reduce reactive losses by shifting advice earlier in the risk chain; applied to sericulture, this could increase cocoon consistency by aligning rearing cycles with short favorable weather windows [18, 21]. This process can be visualised as a continuous advisory cycle where farmer inputs are transformed into monitoring data, analysed by DSS, and delivered as timely digital alerts that guide action, with outcomes feeding back into updated recommendations (Figure 1).

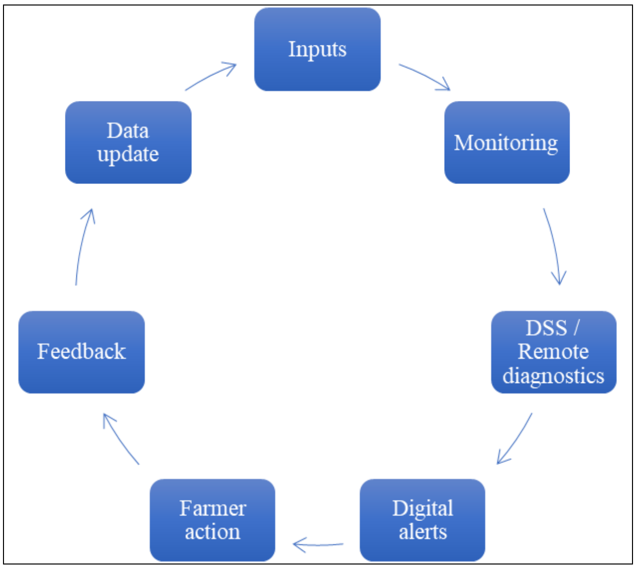

Fig 1: Farm-Level Advisory Cycle showing the iterative flow of inputs through monitoring, decision-support systems, alerts, farmer actions, feedback, and data updates.

Remote sensing and computer-vision tools are already being tested for sericulture problems. High-resolution satellite or Planet Scope imagery can track mulberry biomass and leaf-harvest readiness across fields, helping extension plan leaf supplies and avoid feed shortages [19]. On-farm computer-vision algorithms (lightweight You Only Look Once (YOLO)-style models) can detect dense silkworm clusters, abnormal larval behaviour or counting tasks from phone or embedded cameras, enabling near-real-time diagnostics and faster triage from extension staff [20]. When these diagnostics are integrated into mobile dashboards or SMS/voice alerts for low-connectivity users, they let extension teams monitor many villages simultaneously and act proactively rather than only reacting after losses occur.

3.3 Evidence of adoption and farmer response

Empirical studies across low- and middle-income agricultural systems show that digital extension tools rapidly increase farmers' awareness and technical knowledge, but translating that knowledge into sustained on-farm behaviour change is more complex. Mixed-method research from multiple countries found that tools such as WhatsApp groups, short instructional videos and simple advisory apps improve farmers' ability to recognise pests and diseases, follow time-sensitive operations, and access market information, especially when these tools are moderated by trusted extension agents or lead farmers [8]. However, several rigorous reviews and field studies report that meaningful practice change usually requires the digital advice to be embedded in broader support. Examples include adoption of strain-specific rearing schedules, investment in improved post-cocoon equipment, and changes in mulberry nutrition regimes, which are more likely when combined with hands-on training, field follow-ups, input availability, and linkages to finance or collective purchasing [4, 22].

Structural and social constraints reduce uptake of digital tools. Poor connectivity, limited smartphone ownership, low digital literacy, language mismatches, and weak trust networks limit their usefulness for women, older farmers, and other marginalised groups unless inclusion is explicitly built into the intervention [9, 15]. Studies focused on farmer learning videos and chat-based learning likewise find that while these media raise knowledge quickly, program effectiveness depends on facilitation quality, local relevance of content, and follow-up support to convert learning into changed practice [23, 24]. In short: digital tools are powerful for awareness and diagnosis, but behaviour change in sericulture will depend on integrated delivery models that combine digital advisories with human facilitation, input/market linkages and mechanisms that explicitly address inclusion and local constraints [4, 8].

3.4 Practical Design Lessons for Digital Extension in Sericulture

Evidence from digital agriculture and sericulture tech studies distils key design principles. First, co-design these tools with farmers, using simple language, local dialects, and video demos to support comprehension [4]. Second, blend digital with human facilitation tools perform better when local extension agents or lead farmers moderate chat groups and reinforce messages [8]. Third, favour low-bandwidth formats and multimodal delivery (voice, text, image) to cater to poor connectivity contexts [19]. Lastly, package technical advice with market information, input availability, and access to credit, since standalone advisories often fail to overcome adoption barriers rooted in liquidity or input gaps [25].

Digital platforms ranging from push notifications and instructional videos to remote diagnostics and decision-support tools offer scalable extension channels. Yet, the greatest impact comes when designs address local infrastructure, inclusion, and institutional integration. Without those anchoring features, digital tools raise awareness but fall short in delivering sustained behavioral change on farms [4, 8, 9].

4. Climate-Smart Extension Approaches

Climate change is already altering the agro-ecological conditions that underpin sericulture. Extension systems must therefore move beyond one-off recommendations to integrated, anticipatory, climate-smart approaches that combine agronomy, forecasting, and capacity building [26]. The three pillars below summarise the literature and the practical roles extension can play in making sericulture resilient to current and future climate risks.

4.1 Climate-resilient mulberry cultivation and silkworm rearing practices

Building resilience begins at the crop and farm level. For mulberry, climate-smart recommendations from plant physiology and agronomy research include selecting drought-tolerant genotypes, improving soil moisture retention through mulching and organic amendments, adjusting planting and pruning schedules to avoid heat or drought windows, and applying bio-stimulants or beneficial microbes to sustain leaf yield and quality under stress [27, 28, 29]. At the silkworm level, adaptive practices include shifting rearing calendars to avoid heat spikes, improving microclimate control in rearing houses using shade nets, ventilation, and evaporative cooling where feasible, and enforcing stricter hygiene and quarantine to limit disease flare-ups after climatic stress [5, 30, 31]. Extension agents play a critical role by translating these technical options into locally feasible packages, demonstrating low-cost modifications (e.g., mulching, shade provision), and helping farmers trial tolerant mulberry accessions on-farm before scaling them up. Table 2 summarises key climate-smart practices for mulberry cultivation and silkworm rearing that extension systems can promote to build resilience. Evidence from Sun *et al*. (2020) and Li *et al*. (2022) highlights how targeted breeding and improved management can buffer mulberry against drought and heat stress, which can then be scaled through participatory extension approaches [27, 28].

Table 2: Climate-smart practices for sericulture

Domain	Practices	Reference
Mulberry management	Drought/heat-tolerant genotypes, mulching, organic amendments, optimized pruning schedules	[27, 28, 29]
Silkworm rearing	Adjusted rearing calendars, use of shade nets, microclimate regulation, sanitation and hygiene protocols	[5, 30]
Pest/disease management	Early-warning advisories, community-level surveillance, biocontrol releases, adaptive rearing methods	[18, 31]
Integrated farm resilience	Diversification with intercrops, soil moisture conservation, farmer training on adaptive practices	[32, 33]

4.2 Pest and disease forecasting, surveillance and adaptive management

Climate shifts alter pest life cycles, increase overwintering survival of some pests and change pathogen dynamics. That makes surveillance and early-warning indispensable. Modern pest forecasting combines climate data, pest population monitoring and statistical/machine-learning models to predict outbreak risk and inform timely interventions [18, 31]. In sericulture, extension services can suggest preventive cultural controls like modified rearing dates, sanitation practices, and targeted biocontrol releases instead of depending on expensive curative treatments after losses occur by keeping a close eye on mulberry pests and silkworm diseases over a fine temporal scale [18]. Remote sensing and proximal sensing can help map mulberry biomass and stress hotspots, which supports spatial targeting of surveillance and leaf-supply planning [19]. Computer-vision tools and mobile reporting (photo-based diagnostics) can shorten detection-to-response times, enabling extension staff to triage and advise rapidly [20]. Adaptive management approaches emphasize iterative monitoring, testing of low-cost solutions in farmers' fields, and continuous feedback-based refinement of recommendations, making the surveillance-advice loop a central function of agricultural extension [34].

4.3 Role of extension in risk communication, capacity building and institutional support

Extension is the trusted intermediary between scientific knowledge and farm practice. Climate risk communication must be timely, actionable and tailored to farmers' perceptions and constraints [35]. Effective extension for climate resilience therefore combines awareness raising about changing risks and simple adaptation options, participatory learning through farmer field schools and on-farm trials to build local evidence and trust, co-production of locally relevant advisories that include seasonal forecasts and contingency plans, and facilitation of access to inputs, microfinance, and market linkages so that technical advice is adoptable [35, 36]. Recent empirical work also shows that digital advisory channels (apps, SMS, voice messages) can substantially increase uptake of climate-smart practices if they are integrated into extension workflows and accompanied by capacity building for both extension staff and farmers [32, 36]. In practice, extension services need training in climate science, risk communication techniques, and the use of simple forecasting products. They also need institutional support in terms of budget, staffing, and coordination with meteorological services and research institutions to sustain climate-smart programming [35].

5. Integrated Models: Linking Digital and Climate-Smart Strategies

Integrated models that link digital delivery channels with climate-smart technical content bundle climate information, agronomy, diagnostics, market signals and facilitation into coherent advisory packages that are both timely and locally actionable [37, 38, 39]. Evidence from field trials and platform case studies shows that digital forecasts and decision rules are most effective when mediated by human facilitation and embedded in institutional support [32, 38]. Reviews of digitalization for climate-smart agriculture note that standalone climate data or one-way messaging rarely changes behaviour; measurable uptake requires integrated services that combine localized climate information, decision support, trust building and access to inputs/markets [33, 37].

5.1 Case studies and examples of combined digital and climate advisories

Several peer-reviewed studies document pilots and case studies where digital platforms have been used to deliver climate-informed advisories and decision support to smallholders. Ding *et al*. (2022) evaluated a program that paired ICT advisories with university facilitators and found that combined digital and human facilitation improved the site-specificity and uptake of fertilizer recommendations, showing that human mediation can multiply the impact of digital signals [38]. Borrero *et al*. (2022) present a detailed single-platform case study where a digital data platform aggregated weather, soil and farm data to generate tailored recommendations for smallholders; the study highlights governance, data-sharing and user-interface challenges that determine usability [39]. More specifically on climate adoption, Mao *et al*. (2024) provide empirical evidence from China that digital extension substantially increases adoption of climate-adaptation practices when advisories are localized and linked to extension support [32]. Quarshie *et al*. (2023) review the emergent field of digitalization of climate-smart agriculture and synthesise lessons showing that integration matters: climate data without facilitation has limited effect, while digital tools that incorporate forecasts, localized decision rules and trusted intermediaries produce measurable behavioural change [37]. These case studies collectively show that integrated models work best when digital forecasts and decision rules are translated into actionable, localized recommendations and mediated through human facilitation. A generic pathway for integrating digital tools with climate-smart advisories is illustrated in Figure 2, which outlines how data flows through decision-support systems, digital channels, farmer actions, and feedback loops to extension teams.

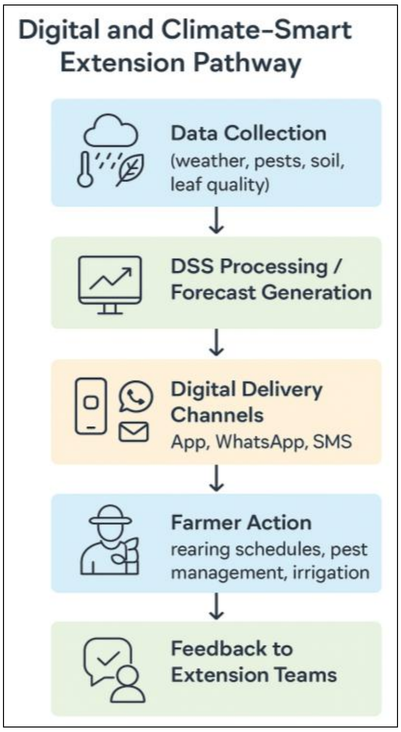

Fig 2: Digital and Climate-Smart Extension Pathway: Flowchart showing how data collection, DSS processing, and digital delivery channels are linked to farmer action and feedback loops.

5.2 Role of participatory extension, farmer field schools and peer networks

Participatory methods remain central to converting digital climate advisories into on-farm action. Farmer Field Schools (FFS) and other participatory learning platforms provide hands-on spaces for testing climate-smart options, co-producing locally relevant advisories, and building farmer confidence to act on digital prompts [40]. Reviews and field studies indicate that FFS approaches help translate seasonal forecasts and climate-informed options into trialled practices because farmers can see and adapt techniques in their specific conditions [35, 40]. Peer networks, including digitally mediated WhatsApp groups and community WhatsApp or Telegram circles, extend the FFS learning loop by allowing rapid sharing of observations, locally validated tips, and short video demonstrations. When these networks are moderated by trained facilitators, they create a continuous feedback loop between digital advisories, field evidence, and adaptive practice. This cycle is illustrated in Figure 3, which shows how Farmer Field Schools, digital peer networks, and on-farm practice interact through feedback loops to generate updated, locally relevant advisories. This approach helps farmers quickly adapt and refine their techniques based on both expert guidance and peer experience [37, 38]. In sericulture, participatory trials could combine on-farm demonstrations of drought-tolerant mulberry genotypes with push advisories such as rearing date alerts aligned to short favorable weather windows, replicating this successful pattern.

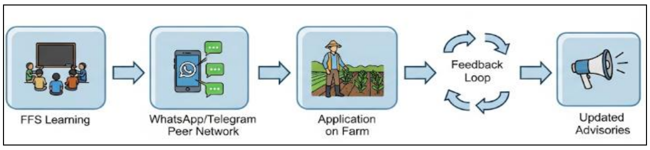

Fig 3: Farmer Field School (FSS) and Digital Integration: Linking participatory learning, peer networks, on-farm application, feedback, and updated advisories.

5.3 Policy support and institutional innovations for scaling integrated models

Scaling integrated digital and climate models requires policy and institutional enablers that ensure data flows, sustain facilitation capacity, and align incentives across agriculture, meteorology and extension systems. Key policy measures include institutional linkages between meteorological services and extension agencies, funding lines for sustained facilitator training, standards for data governance and interoperability, and mechanisms to subsidise last-mile access for marginalized farmers [33, 39]. Research shows that where national programmes provide interoperable platforms and support human facilitation, digital climate advisory services (DCAS) reach more users and translate into practice change [32, 37]. The literature also flags governance risks: data ownership, transparency of decision rules, and equity in access are recurring concerns that policy must address to prevent digital exclusion or unintended harms [39]. Finally, financing models that bundle digital advisories with credit, input supply and market aggregation increase the perceived value of advice and improve adoption rates [32, 33].

6. Conclusion and Future Prospects

This review underscores that sericulture's future hinges on strengthening digital extension and climate-smart practices through interventions that are practical, inclusive, and usable by farmers. Current tools like decision-support systems, peer-to-peer messaging, and forecasting models help improve response times and adaptation. Yet, persistent challenges, such as poor infrastructure in remote areas, lack of integration with financial and market systems, and digital literacy barriers still limit meaningful adoption. Effective extension must therefore go beyond technical advice and embed digital tools within participatory models, facilitated by trusted local agents and aligned with institutional support systems.

Looking ahead, future research and extension efforts should deepen innovation in several interlinked areas. First, enhance decision-support systems (DSS) with localized data, easier interfaces, offline access, and integration into policy and subsidy frameworks, as seen in broader agroecology contexts [21]. Second, strengthen climate-resilient extension by linking indigenous knowledge with conventional forecasting in farmer field schools to build trust and relevance [41]. Third, explore emerging technologies like drone-assisted spraying and monitoring to ease labor constraints and improve precision, while developing ethical, regulatory, and operational frameworks [42]. Finally, align extension with broader resilience goals, integrating pest forecasting, participatory learning, and institutional reforms to help sericulture systems thrive under climate pressure [43].

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