Review Article

**Sericulture as a Sustainable Agroforestry System: Enhancing Soil Health, Biodiversity, and Resource Efficiency**

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ABSTRACT

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| Sericulture offers a unique model for integrating economic productivity with ecological sustainability when embedded within agroforestry systems. This review examines the role of mulberry-based sericulture in enhancing soil health, supporting biodiversity, and improving resource efficiency. Perennial growth, flexible management, and biomass inputs of mulberry contributes to soil conservation, carbon sequestration, nutrient cycling, and microclimate regulation. Integration with companion crops and recycling of sericulture by-products further strengthens circular nutrient pathways and reduces reliance on external inputs. Sericulture-based agroforestry also promotes habitat provision, pollinator activity, pest regulation, and landscape connectivity, delivering measurable ecosystem services alongside rural livelihood benefits. However, trade-offs between silk production, intercropping, and ecosystem functions require context-specific management, informed by site conditions, pruning regimes, and farmer knowledge. Future research should focus on long-term field trials that evaluate ecological, productive, and socioeconomic outcomes, while policies and incentives should encourage adoption of multifunctional land-use designs. Overall, sericulture-centred agroforestry represents a viable strategy for climate-resilient, sustainable rural development. |

*Keywords: Sericulture, Agroforestry, Soil Health, Resource Efficiency, Ecosystem Services*

1. INTRODUCTION

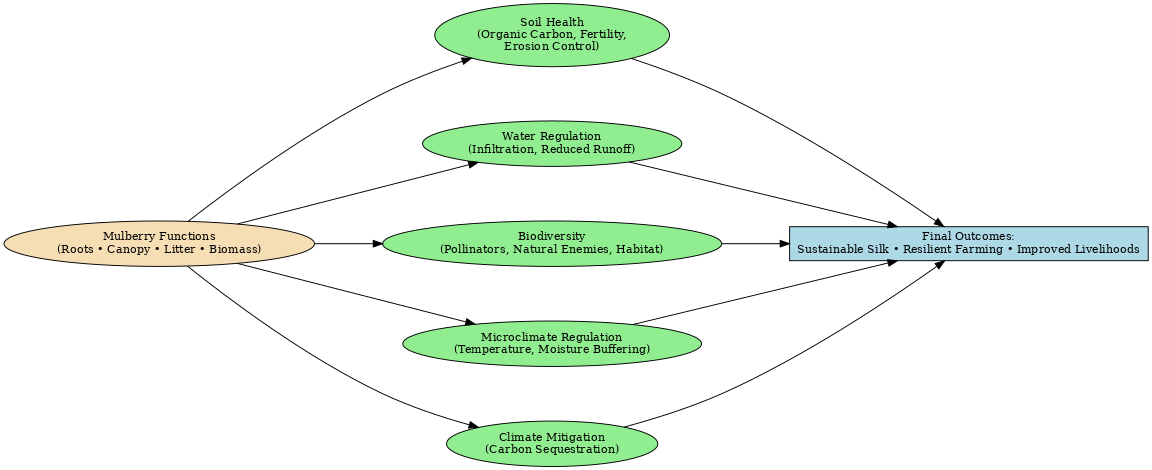
Sericulture is a significant agro-based enterprise that supports rural livelihoods through employment generation, income creation, and integration into global textile value chains (Baciu *et al.,* 2023). Beyond its role in livelihoods, sericulture’s integration with agroforestry highlights additional ecological and production benefits, making it a model for sustainable land-use practices. Sericulture systems exhibit features that align closely with agroforestry, including perennial components, intercropping opportunities, and the capacity to deliver ecological benefits alongside fibre production, enhancing production efficiency, soil conservation, biodiversity support, and broader ecosystem functions (Gangopadhyay, 2024; Van Noordwijk, 2021a).

Environmental pressures like land degradation, soil erosion, freshwater stress, and increasing climatic variability are placing conventional mono-crop and short-rotation systems under strain. Agroforestry approaches that combine woody perennials with crops can reduce erosion, increase soil organic carbon, improve microclimates, and strengthen system resilience to extreme weather (Yang *et al.,* 2024). Mulberry, in particular, is a fast-growing multipurpose species whose root systems, leaf litter inputs and canopy architecture contribute to soil conservation, carbon sequestration and microclimate buffering when managed within diversified farming systems (Baciu *et al.,* 2023; Kaushal *et al.,* 2024).

From a sustainability perspective, combining sericulture with agroforestry can deliver several complementary benefits. It provides opportunities for resource efficiency, as land equivalent ratios often improve under tree–crop integration, and trees contribute continuous organic matter that supports soil fertility and reduces reliance on synthetic fertilizers (van Noordwijk, 2021a). Agroforestry designs that include mulberry can also support biodiversity and ecosystem services at the farm scale by providing habitat, stabilizing soils, and moderating water flows, while creating diversified income streams for rural households (Yang *et al.,* 2024). In addition, sericulture by-products and on-farm recycling (leaf litter, pupal waste, pruning residues) can be incorporated into circular nutrient pathways to further reduce external inputs and waste (Fatimaa+ *et al.,* 2024).

Despite these potentials, the trade-offs between silk production, companion crops, and ecosystem services depend on local site conditions, canopy and pruning regimes, intercropping choices, and farmer knowledge; these require context-specific empirical evaluation (Kaushal *et al.,* 2024). Policy, market incentives and extension services also shape whether smallholders adopt integrated designs, and they influence how ecosystem benefits are measured, valued and rewarded (van Noordwijk, 2021a).

This review examines sericulture as a model for sustainable agroforestry, focusing on mulberry’s ecological functions, soil and resource management, biodiversity contributions, and practical strategies for improving efficiency and farmer resilience. The goal is to provide a compact, evidence-based foundation for applying sericulture-centred agroforestry to strengthen environmental sustainability and rural livelihoods. To visualize these linkages, Figure 1 illustrates the ecosystem services delivered by mulberry-based agroforestry and their contribution to sustainable sericulture systems.



**Figure 1. Ecosystem services pathway of mulberry-based agroforestry and their role in sustaining sericulture systems.**

1. **AGROFORESTRY DESIGN AND MULBERRY INTEGRATION**

Mulberry functions as a keystone component in sericulture-centred agroforestry because it combines perennial biomass production with flexible management that allows effective integration with annual crops and trees (Kaushal *et al.,* 2024; Zhang *et al.,* 2024). When planned as part of an agroforestry design, mulberry contributes structural complexity, regular leaf biomass inputs, and a year-round source of organic material that together support soil stability and nutrient cycling in mixed farming landscapes (Kaushal *et al.,* 2024; Xiao *et al.,* 2023).

Several mechanisms underlie mulberry’s ecosystem contributions. Its root architecture and canopy reduce surface runoff and trap sediments on sloping lands, limiting erosion and improving water infiltration (Kaushal *et al.,* 2024). At the same time, mulberry produces high above- and below-ground biomass, which increases soil organic carbon when litter and pruning residues are returned to the field; this contributes to both soil fertility and on-farm carbon sequestration (Zhang *et al.,* 2024; Kumar *et al.,* 2024a). These effects are strongest where pruning, litter management and intercropping are deliberately aligned with soil conservation goals (Kaushal *et al.,* 2024).

Mulberry integration is most effective when companion species are chosen to reduce competition and enhance complementarities. Intercropping with legumes, vegetables, or shallow-rooted cereals can increase land-use efficiency and supply nitrogen through biological fixation, thereby lowering reliance on synthetic fertilizers (Rafiqui *et al.,* 2023; Chamkhi *et al.,* 2022). Empirical studies show that carefully managed mulberry-legume systems can maintain or even raise total system yield per unit area while improving soil nutrient status and microbial activity (Islam *et al.,* 2023; Xiao *et al.,* 2023). At the microbial level, intercropping and companion planting alter soil microbial community composition, enhancing nutrient cycling and soil health, which supports sustained productivity in agroforestry systems (Gao & Zhang, 2023; Liu *et al.,* 2024).

Canopy and pruning management are critical tools to balance mulberry’s benefits with its potential for shading or below-ground competition. Regular canopy regulation like timed pruning, row spacing decisions, and rotational cutting can maintain light availability for understorey crops and control root competition, while producing usable biomass (for feed, fuel, or mulch) that feeds circular nutrient flows on the farm (Kaushal *et al.,* 2019; Kaushal *et al.,* 2024). Studies also highlight the value of matching planting density and cultivar choice to the local cropping mix; low, multi-stem forms and periodic coppicing are practical options where intensive intercropping is desired (Rafiqui *et al.,* 2023).

Designing mulberry-based agroforestry therefore requires explicit trade-off assessment. High mulberry density maximizes leaf yield for sericulture but may reduce understorey crop returns and alter the microclimate, while lower tree density favors intercrops and multi-product use but reduces total leaf output and carbon capture (Kaushal *et al.,* 2024; Zhang *et al.,* 2024). The best designs are context specific, combining local agronomic knowledge, site conditions (soil type, slope, rainfall), and livelihood priorities to select companion species, spacing, and pruning regimes that optimize both production and ecosystem services. To illustrate these options, Table 1 summarizes common mulberry-based agroforestry designs, their yield potential, ecosystem benefits, and associated trade-offs reported in recent studies.

Mulberry can act as a multifunctional anchor in agroforestry systems when integrated with complementary crops and managed through tailored canopy and residue practices. Such integration improves land-use efficiency, promotes soil conservation, enhances microbial and plant community functions, and contributes to on-farm carbon storage. To scale these benefits, research should prioritize field trials that quantify production–service trade-offs across agroclimatic zones and test management packages that farmers can adopt with minimal additional labour or input costs (Kaushal *et al.,* 2024; Xiao *et al.,* 2023; Gao & Zhang, 2023).

## **Table 1. Agroforestry Design Options with Mulberry**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Agroforestry Design Type** | **Mulberry Density** | **Companion Crops** | **Leaf Yield / Biomass Potential** | **Soil / Ecosystem Service Effect** | **Notes / Trade-offs** | **Reference** |
| High-density rows | High | Low or none | Max leaf yield | Moderate soil conservation, less understorey light | May reduce intercrop yield | Kaushal *et al.,* 2024 |
| Medium-density + intercrops | Medium | Legumes, vegetables | Moderate yield | Improved soil fertility, N fixation, microbial activity | Requires careful pruning | Rafiqui *et al.,* 2023 |
| Low-density multi-stem | Low | Cereals, vegetables | Lower yield | Maximizes intercrop yield, carbon storage | Less total leaf biomass | Zhang *et al.,* 2024 |

1. **SOIL HEALTH AND FERTILITY MANAGEMENT**

Healthy soils are the foundation of productive mulberry gardens and resilient sericulture systems. Sericulture influences soil physical, chemical and biological properties through management of mulberry stands, leaf harvesting, irrigation practices, and the handling or reuse of sericulture by-products (Zhong *et al.,* 2020; Kaushal *et al.,* 2024). When integrated into agroforestry designs, mulberry components can contribute to long-term soil organic matter accumulation and improved structure, but these outcomes depend strongly on residue management, input regimes and local edaphic conditions (Zhang *et al.,* 2024; Lamani *et al.,* 2024).

* 1. **Effects on soil physical and chemical properties**

Mulberry plantations, particularly when managed with conservation measures such as contour planting, hedgerows and coppicing, help reduce erosion and surface runoff and thereby conserve topsoil and associated nutrients (Kaushal *et al.,* 2024; Zhong *et al.,* 2020). Studies also report improved water infiltration and reduced bulk density under mulberry-based systems compared with continuous annual cropping (Zhong *et al.,* 2020). Recycling pruning residues and leaf litter increases soil organic carbon and nutrient pools, enhancing cation exchange capacity and long-term nutrient retention (Kaushal *et al.,* 2024; Zhang *et al.,* 2024).

* 1. **Biological activity and microbial function**

Soil microbial indicators respond positively to organic amendments and diversified cropping. Practices such as composting sericulture wastes, using green manures and integrating legume intercrops increase microbial biomass, enzyme activity and nutrient mineralization rates, all of which enhance mulberry nutrition and soil fertility (Shen *et al.,* 2024; Jothimani *et al*., 2024). Improved microbial functioning also contributes to soil aggregation and stabilization of organic matter, reinforcing the resilience of these systems (Shen *et al.,* 2024).

* 1. **Sustainable soil management practices for sericulture systems**

A combination of organic nutrient sources, conservation tillage, and crop rotation/intercropping is recommended to maintain productivity while reducing chemical inputs. Organic amendments such as farmyard manure, vermicompost and composted sericulture waste improve soil nutrients and plant performance and lower the dependence on synthetic fertilizers (Jothimani *et al.,* 2024; Bora *et al.,* 2025). Biochar and other carbon-rich amendments can further stabilize soil carbon and modify nutrient dynamics, although their effects vary by biochar type, rate and soil context (Lamani *et al.,* 2024). Integrating legumes or green manures within the mulberry cropping matrix supplies biologically fixed nitrogen and enhances soil cover, reducing erosion and improving nutrient cycling (Zhong *et al.,* 2020; Altman & Farrell, 2022).

* 1. **Managing risks and trade-offs**

Not all sericulture practices are inherently beneficial for soils. Irrigation with untreated silk-reeling effluents or improper disposal of processing wastes can alter soil pH, salinity and heavy metal burdens, potentially degrading fertility (Kiruthika *et al.,* 2024). High mulberry density and poor pruning practices may also increase competition for water and nutrients, reducing understorey crop performance and concentrating erosive flows where canopy cover is insufficient (Kaushal *et al.,* 2024). Thus, site-specific assessment and adaptive management are essential.

* 1. **Practical recommendations for sustained productivity**

Based on recent field studies and reviews, practical recommendations include, returning pruning residues as mulch or compost; adopting vermicomposting or co-composting to stabilise sericulture wastes and improve nutrient availability; introducing legume intercrops or green manures to enhance nitrogen supply; using contour hedgerows and coppicing on slopes to limit erosion; and testing biochar or similar soil conditioners in small trials before scale-up (Kaushal *et al.,* 2024; Lamani *et al.,* 2024; Shen *et al.,* 2024; Jothimani *et al.,* 2024). These practices improve soil health metrics while aligning with resource-efficient agroforestry goals.

Soil health in sericulture-based agroforestry depends on how organic matter is recycled, inputs are balanced and erosion is controlled. When sustainable practices are implemented, these systems can build soil organic matter, foster beneficial microbial communities and maintain productivity over time. Continued trials across different agroclimatic zones and careful monitoring of soil indicators will help refine best practices that are both effective and practical for farmers (Kaushal *et al.,* 2024; Shen *et al.,* 2024).

1. **BIODIVERSITY AND ECOSYSTEM SERVICES**

Sericulture-based agroforestry can deliver measurable biodiversity and ecosystem-service benefits at field and landscape scales when mulberry is managed as part of diversified farming mosaics. These benefits operate through three linked pathways, including the provision of habitat and resources for flora and fauna, such as pollinators and natural enemies, the enhancement of ecosystem functions such as nutrient cycling and microclimate regulation, and the contribution of on-farm features to broader habitat networks that support conservation objectives (Kuyah *et al.,* 2019; Yang *et al.,* 2024).

* 1. **Habitat provision and faunal diversity**

Mulberry stands and associated agroforestry elements create structural and trophic resources that sustain a range of species. The perennial woody component and its understorey provide nesting sites, foraging substrate and refuge for birds, arthropods and small mammals relative to open-field monocultures (Kuyah *et al.,* 2019; Lin *et al.,* 2024). In mixed systems, increased plant structural complexity correlates with higher insect and bird richness and with greater abundance of beneficial arthropods (predators and parasitoids) that contribute to biological pest control (Yang *et al.,* 2024; Kuyah *et al.,* 2019). Several recent case studies from mulberry-dominated landscapes show that agroecosystems combining woody and herbaceous components maintain greater pollinator activity and higher functional diversity than simplified cropping systems (Fatimaa+ *et al.,* 2024; Lin *et al.,* 2024).

* 1. **Pollinators and top-down ecosystem regulation**

Pollinators benefit from temporal and spatial heterogeneity of floral resources in agroforestry mosaics. Even if mulberry itself is wind- or insect-pollinated to varying degrees, the inclusion of companion flowering species, hedgerows or understory plantings within mulberry systems supports continuous nectar and pollen availability across seasons, stabilizing pollinator communities and pollination services for adjacent crops (Yang *et al.,* 2024; Kumar *et al.,* 2024b). Semi-natural habitats increase both pollinator activity and natural enemy abundance, delivering simultaneous pollination and pest-control services (Alarcon-Segura *et al.,* 2025).

* 1. **Nutrient cycling and soil biological functions**

Trees and perennial shrubs in agroforestry increase organic-matter inputs through leaf litter, root turnover and pruning residues. These inputs stimulate soil microbial activity and drive nutrient retention and cycling processes that improve soil fertility and reduce nutrient losses compared with annual-only systems (Kuyah *et al.,* 2019; Udawatta & Gantzer, 2022). Research from mulberry-based systems indicates that returning pruning residues and pupal/leaf waste to the soil increases soil organic carbon and microbial biomass, with positive effects on nutrient availability for both tree and companion crops (Kaushal *et al.,* 2024; Fatimaa+ *et al.,* 2024).

* 1. **Microclimate stabilization and watershed benefits**

The canopy and litter of woody components moderate ground-level temperature, reduce evapotranspiration extremes, and buffer soil moisture fluctuations, creating a more favourable microclimate for both plants and soil organisms (Kuyah *et al.,* 2019; Udawatta & Gantzer, 2022). On sloping land, mulberry rows or contour plantings reduce runoff velocity, increase infiltration and trap sediments, actions that protect downstream water quality and support landscape-level erosion control (Kaushal *et al.,* 2024; Lin *et al.,* 2024).

* 1. **Habitat connectivity and conservation value**

When implemented across farms and along riparian corridors, mulberry-based agroforestry elements add semi-natural habitat patches and stepping stones that enhance landscape connectivity. This increases the effective area available to species that require woody vegetation, and it can contribute to regional conservation goals without requiring full land-use conversion to forest (Lin *et al.,* 2024; Yang *et al.,* 2024). Such multi-functional land uses reconcile production and conservation aims, particularly where smallholder landscapes dominate and strictly protected areas are limited.

* 1. **Limits, trade-offs and research needs**

Not all biodiversity outcomes are uniformly positive. Trade-offs arise when high-density woody plantings reduce understorey diversity or shade out income-bearing intercrops, and when poorly managed systems accumulate pests or diseases that affect both tree and non-tree components (Kaushal *et al.,* 2024; Kuyah *et al.,* 2019). Empirical studies that quantify these trade-offs across agroclimatic zones are scarce. Future research should prioritize replicated field trials that measure multi-trophic biodiversity responses, pollination and pest-regulation services, and the net effects on farm productivity and farmer livelihoods (Yang *et al.,* 2024; Udawatta & Gantzer, 2022).

Sericulture-based agroforestry offers opportunities to integrate biodiversity goals with rural development by linking habitat creation, soil improvement, and diversified income streams (Kuyah *et al.,* 2019; Lin *et al.,* 2024). To maximize these co-benefits, future research should prioritize long-term field studies, quantify trade-offs across ecological and economic dimensions, and guide policies that reward ecosystem-service outcomes (Kaushal *et al.,* 2024; Yang *et al.,* 2024; Udawatta & Gantzer, 2022).

1. **RESOURCE EFFICIENCY AND ENVIRONMENTAL SUSTAINABILITY**

Agroforestry systems based on sericulture provide solutions to integrate mulberry with complementing farm enterprises, improving resource efficiency and reducing environmental consequences. These systems encourage the circular use of sericulture byproducts, maximise the use of water, land, and fertilisers, and enhance climate resilience through a variety of ecological processes.

* 1. **Efficient use of water, land and nutrients**

Water scarcity is a real constraint for scaling moriculture in many regions and can create competition with food crops unless irrigation and crop choices are matched to local water budgets (Ricciardi *et al.,* 2021). Precision irrigation and micro-irrigation (drip) systems substantially increase water-use efficiency (WUE) in mulberry stands compared with surface irrigation, and fertigation, combined irrigation plus fertilizer application, improves nutrient-use efficiency while maintaining or increasing leaf yield (Mahesh *et al.,* 2022; Ranjitha & Chandrashekhar, 2021). When mulberry is integrated into agroforestry, careful spacing, cultivar selection and canopy management (pruning/coppicing) raise land-equivalent ratios by permitting productive intercrops beneath or between mulberry rows, thereby increasing output per unit land and improving overall resource productivity (Kaushal *et al.,* 2024; Altman & Farrell, 2022).

Practical implications for resource efficiency include: (a) adopt drip irrigation with scheduled deficit or regulated deficit strategies to match crop demand and reduce evaporation losses; (b) combine drip with fertigation to deliver nutrients in smaller, more frequent doses that reduce leaching and increase uptake; and (c) plan tree density and pruning cycles to allow profitable intercrops where appropriate, increasing land-use productivity without compromising soil or water services (Kaushal *et al.,* 2024; Ricciardi *et al.,* 2021; Mahesh *et al.,* 2022).

* 1. **Waste management and recycling of sericulture by-products**

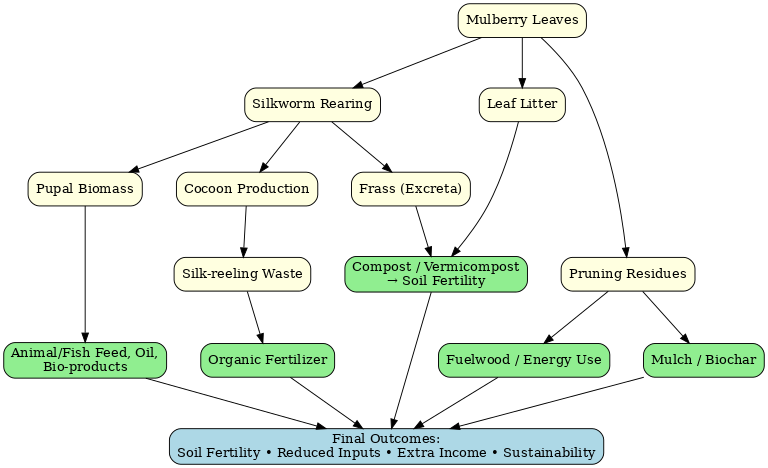
Sericulture generates several organic by-streams that can be recycled on-farm or valorized as products, such as leaf residues, rearing bed refuse and frass (silkworm excreta), pupal biomass and silk-reeling waste. These streams are rich in nutrients and organic matter and, when processed appropriately, become valuable inputs rather than wastes (Beesigamukama *et al.,* 2022; Zhou *et al.,* 2022). Composting and vermicomposting of rearing residues and frass produce stable soil amendments that raise soil organic carbon, supply plant-available nutrients, and improve soil biological activity (Beesigamukama *et al.,* 2022; Suraporn *et al.,* 2024).

Spent pupae represent a high-protein, high-lipid biomass that can be processed into animal feed ingredients, oil, or fermented products; this both reduces disposal problems and provides alternative income streams (Zhou *et al.,* 2022; Rodríguez-Ortiz *et al.,* 2024). Microbial and safety issues must be managed through hygienisation, drying, controlled composting, or heat treatment to meet feed or fertilizer standards. However, systematic reviews and experimental studies show multiple viable valorisation routes that align with circular-economy principles (Beesigamukama *et al.,* 2022; Rodríguez-Ortiz *et al.,* 2024). The main sericulture by-products, their processing requirements, and potential uses are summarized in Table 2. To complement this, Figure 2 illustrates the circular flow of these by-products and their role in nutrient recycling and system sustainability.

Recommended on-farm actions include segregate by-streams at source, apply proven composting or vermicomposting protocols for frass and leaf residues, evaluate low-cost drying/preservation for pupae destined to feed or processing, and explore small-scale anaerobic digestion or protein extraction where local markets and regulations permit. These measures close nutrient loops, reduce dependence on external fertilizers, and add resilience to farm incomes (Beesigamukama *et al.,* 2022; Rodríguez-Ortiz *et al.,* 2024).

## **Table 2. Recycling of Sericulture By-products and Their Uses**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **By-product** | **Potential Use** | **Processing Required** | **Nutrient / Organic Matter Content** | **Benefits** | **Reference** |
| Pruning residues / leaf litter | Mulch, compost | Composting / direct incorporation | High C and N | Improves soil organic matter, reduces erosion | Kaushal *et al.,* 2024 |
| Silkworm frass | Fertilizer / vermicompost | Vermicomposting / composting | High N, P, K | Enhances microbial activity and nutrient cycling | Beesigamukama *et al.,* 2022 |
| Pupal biomass | Animal feed, oil extraction | Drying / processing / fermentation | High protein and lipid | Provides alternative income, reduces waste | Rodríguez-Ortiz *et al.,* 2024 |
| Silk-reeling waste | Compost / biofertilizer | Co-composting | High organic content | Improves soil fertility, circular nutrient use | Suraporn *et al.,* 2024 |



**Figure 2. Circular Flow of Sericulture By-products and Nutrient Recycling**

* 1. **Climate resilience and mitigation potential of integrated systems**

Mulberry-based agroforestry has demonstrable potential for carbon sequestration through above- and below-ground biomass accumulation and soil organic matter enhancement, particularly where pruning residues and litter are returned to the soil (Kaushal *et al.,* 2024; Altman & Farrell, 2022). Integrated systems also provide microclimate buffering, reducing temperature extremes and conserving soil moisture, which increases resilience to heat and drought events (Kaushal *et al.,* 2024). At landscape scale, agroforestry elements (mulberry rows, contour plantings, buffers) reduce erosion and stabilize hydrological flows, supporting both mitigation and adaptation goals (Kaushal *et al.,* 2024; Ricciardi *et al.,* 2021).

However, trade-offs exist like high-density moriculture focused solely on leaf yield may sequester carbon but could intensify water demand; conversely, low-density multifunctional designs may reduce per-tree yields but increase total ecosystem service provision and livelihood diversification (Altman & Farrell, 2022). Policy incentives such as payments for ecosystem services and carbon finance, along with extension services that value co-benefits, are important levers to encourage designs that balance production with climate goals (Kaushal *et al.,* 2024; Altman & Farrell, 2022).

1. **CONCLUSION AND FUTURE PERSPECTIVES**

Sericulture-integrated land-use systems offer a pathway to combine rural livelihood opportunities with ecological sustainability. By embedding mulberry within diversified farming landscapes, these systems enhance soil fertility, conserve water, contribute to carbon sequestration, and provide habitat that supports biodiversity (Kaushal *et al.,* 2024; Yang *et al.,* 2024). Socioeconomically, they generate steady income, employment, and value-added opportunities while aligning with sustainable intensification goals (Baciu *et al.,* 2023). Recycling of sericulture by-products further strengthens circular nutrient flows and reduces reliance on external inputs, positioning these systems as promising models for climate-resilient farming (Beesigamukama *et al.,* 2022; Rodríguez-Ortiz *et al.,* 2024).

Despite these benefits, several gaps remain. Trade-offs between leaf production, companion crop yields, and ecosystem services require long-term field trials across agroecological zones (Kaushal *et al.,* 2024). Adoption is also shaped by policy support, extension networks, and access to carbon or biodiversity markets, which remain uneven in many regions (Van Noordwijk, 2021b). Future research should prioritize integrated assessments of productivity, soil and biodiversity outcomes, alongside socioeconomic analyses of farmer adoption. At the policy level, incentives that recognize ecosystem services and promote farmer-friendly innovations will be key to scaling sericulture-integrated land-use systems for environmental sustainability and rural development (Yang *et al.,* 2024; Alarcón-Segura *et al.,* 2025).

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