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Biological inputs for climate smart sericulture: current status, mechanisms and future prospects: A review

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Abstract

Sericulture, based on mulberry (*Morus* spp.) cultivation and silkworm (*Bombyx mori* L.) rearing, is a high value agro-industry vital for rural livelihoods and silk production. However, long-term dependence on chemical fertilizers and pesticides has resulted in soil degradation, declining leaf quality, and environmental concerns. Biological inputs such as biofertilizers, organic amendments, microbial consortia, and biopesticides provide sustainable alternatives for enhancing mulberry productivity while safeguarding ecosystem health. These inputs improve nutrient mobilization, soil physical and chemical properties, leaf biochemical quality, and plant physiological processes, while enhancing stress tolerance, pest suppression, and induced resistance. Evidence from multi-location demonstrations and farmer-participatory trials indicates that biologically managed systems increase leaf yield, improve silkworm growth and cocoon quality, and generate favorable economic returns through reduced chemical input costs. Integration of biological inputs also supports climate-smart sericulture by improving soil moisture retention, carbon sequestration, and system resilience under variable agro-climatic conditions. Despite these advances, challenges remain, including inconsistent field performance, quality standardization issues, limited mechanistic understanding, and adoption barriers. Future priorities should focus on long-term field validation, mechanistic plant-microbe-pest studies, formulation optimization, and participatory extension strategies. This review synthesizes current evidence to guide researchers, extension personnel, and farmers toward biologically based, sustainable, and climate-resilient sericulture systems.

Keywords: Biofertilizers, biopesticides, microbial consortia, mulberry, climate-smart sericulture, leaf quality, pest management, sustainable agriculture

Introduction

Sericulture, the cultivation of mulberry (*Morus* spp.) for silkworm (*Bombyx mori* L.) rearing, represents a high-value agro-based industry that contributes substantially to rural livelihoods, employment generation, and global silk production. India accounts for approximately 18% of worldwide silk output, with Karnataka, Tamil Nadu, Andhra Pradesh, and West Bengal as major production hubs (Sengupta *et al.*, 2000; Dandin *et al.*, 2003a) ^[31, 9]. The quality and yield of mulberry leaves, the primary feed for silkworms, directly influence larval growth, cocoon characteristics, and overall silk productivity. Leaf yield and quality are strongly governed by soil fertility, nutrient availability, water status, and pest management strategies. Conventional reliance on chemical fertilizers and pesticides, however, has led to soil degradation, reduced microbial diversity, and risks of pesticide residues, compromising sustainability in sericulture systems (Datta, 2005a; Govindan *et al.*, 2007b) ^[12, 17]. Biological inputs, including biofertilizers, organic amendments, microbial consortia, and biopesticides, have emerged as sustainable alternatives that enhance mulberry productivity while maintaining ecosystem health. These inputs improve nutrient mobilization, soil structure, water retention, and plant physiological processes, while simultaneously reducing pest incidence and enhancing stress tolerance, thereby aligning with the principles of climate-smart agriculture (Ramesh *et al.*, 2012; Bhattacharya *et al.*, 2020) ^[27, 5]. Integrated application of biological inputs has been reported to increase leaf yield, improve protein content and digestibility, reduce chemical input costs, and enhance economic returns in mulberry cultivation (Sannappa *et al.*, 2014; Singh *et al.*, 2023) ^[30, 33].

Despite growing research, an integrated synthesis of mechanisms, field applications, climate-smart outcomes, and economic viability of biological inputs in sericulture remains limited. Critical gaps persist in understanding interactions among soil microbiota, mulberry physiology, pest dynamics, and silkworm performance under biologically managed systems. This review synthesizes current evidence on mechanisms, impacts, and practical advances of biological inputs in mulberry ecosystems, while identifying key challenges and research priorities. The analysis provides a concise framework to guide sustainable and climate-smart sericulture practices.

Current status of biological inputs under mulberry ecosystem

Biofertilizers and organic amendments

Biofertilizers and organic amendments constitute the cornerstone of sustainable nutrient management in mulberry-based sericulture, delivering long-term benefits to soil health, leaf productivity, and silkworm performance. Since the early 2000s, studies have demonstrated that biofertilizers such as *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), and arbuscular mycorrhizal fungi (AMF) enhance nutrient availability through biological nitrogen fixation, solubilization of insoluble phosphates, potassium mobilization, and improved root nutrient uptake (Sengupta *et al.*, 2000; Dandin *et al.*, 2003a) [31, 9]. These microbial inputs further stimulate soil enzymatic activity, microbial biomass carbon, and rhizosphere functional diversity, thereby improving nutrient use efficiency and sustaining mulberry leaf yield under reduced chemical fertilizer inputs (Datta, 2005b; Govindan *et al.*, 2007a) [13, 16]. Organic amendments such as farmyard manure, vermicompost, composted sericulture wastes, mulberry litter residues, and press-mud complement biofertilizers by increasing soil organic carbon, cation exchange capacity, aggregate stability, and moisture retention, which together enhance nutrient retention and synchronized nutrient release with crop demand (Ramesh *et al.*, 2012; Thangavelu *et al.*, 2016) [27, 36]. Integrated application of biofertilizers with organic amendments has consistently resulted in higher mulberry leaf yield, improved nitrogen, phosphorus, and potassium content, increased crude protein and chlorophyll concentration, and superior silkworm growth, larval survivability, and cocoon yield compared with sole application of inorganic fertilizers (Sannappa *et al.*, 2014; Rahmathulla *et al.*, 2019) [30, 26]. During the last decade, liquid biofertilizers and microbial consortia-based formulations combined with organic amendments have gained prominence due to improved microbial viability, field adaptability, and stable performance under variable climatic conditions (Bhattacharya *et al.*, 2020) [5]. Recent reviews further emphasize that such integrated approaches enhance productivity while contributing to climate resilience through improved soil carbon sequestration and reduced dependence on chemical fertilizers (Borah *et al.*, 2025a; Ahammed, 2025) [7, 1]. Despite substantial progress, challenges related to product quality standardization, region-specific validation, and limited long-term multi-location studies remain in sericulture systems.

Bio pesticides and biological control

Biopesticides and biological control have become integral to sustainable and climate-smart sericulture by enabling effective pest and disease management while minimizing chemical residues on mulberry leaves and adverse effects on silkworm health. Since the early 2000s, studies have demonstrated the

efficacy of microbial biopesticides such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium lecanii*, nucleopolyhedroviruses (NPVs), and entomopathogenic nematodes against major mulberry pests, including leaf webbers, semiloopers, thrips, mites, and defoliators (Sengupta *et al.*, 2000; Dandin *et al.*, 2003b) [31, 10]. These agents suppress pests through mechanisms such as toxin production, cuticle penetration, and host-specific pathogenicity, ensuring effective control with minimal non-target impacts (Datta, 2005a) [12]. Botanical biopesticides, particularly neem (*Azadirachta indica*) based formulations, pongamia, and other plant-derived extracts, are widely adopted due to their antifeedant, repellent, and growth-regulating properties, along with proven safety to silkworms (Anna Kaushik *et al.*, 2025; Shetty *et al.*, 2025) [3, 34]. Biological control using parasitoids such as *Trichogramma* spp. and *Nesolynx thymus*, and predators including coccinellids and chrysopids, has shown notable success in suppressing key pests, especially the uzi fly (*Exorista bombycis*), under both experimental and farmer field conditions (Gangadhar *et al.*, 2012; Sannappa *et al.*, 2014) [14, 30]. Integrated pest management (IPM) modules combining biopesticides, biological control agents, and cultural practices consistently reduce pest incidence, lower defective cocoon percentage, and improve cocoon yield compared with chemical-based approaches (Rahmathulla *et al.*, 2019) [26]. Recent syntheses highlight that advances in formulation technologies such as liquid, oil-based, and encapsulated biopesticides, and multifunctional microbial consortia have enhanced shelf life, field efficacy, and performance stability under variable climatic conditions (Bhattacharya *et al.*, 2020; Gundreddy *et al.*, 2024) [5, 18]. Collectively, evidence accumulated over two decades supports biopesticides and biological control as environmentally safe, economically viable, and silkworm-compatible alternatives for sustainable sericulture.

Microbial consortia and novel formulations

Microbial consortia and novel biological formulations represent a major advancement over single-strain inoculants in mulberry-based sericulture, as they provide multiple, complementary functions simultaneously. Early studies showed that combined inoculation of nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and plant growth-promoting rhizobacteria (PGPR) resulted in greater nutrient availability, enhanced soil microbial activity, and higher mulberry leaf yield than individual microbial applications (Dandin *et al.*, 2003a; Sannappa *et al.*, 2010) [3, 30]. Typically, microbial consortia comprise functionally diverse organisms such as *Azotobacter*, *Azospirillum*, phosphate- and potassium-solubilizing bacteria, *Bacillus* spp., *Pseudomonas* spp., and arbuscular mycorrhizal fungi, which collectively promote nutrient mobilization, phytohormone production, and efficient root–soil interactions (Gyaneshwar *et al.*, 2002; Govindan *et al.*, 2007a) [19, 16]. Evidence from the last decade indicates that consortia-based biofertilizers significantly enhance soil enzyme activities, microbial biomass carbon, nutrient use efficiency, and mulberry leaf biochemical quality, particularly crude protein and chlorophyll content, leading to improved silkworm growth and cocoon productivity (Sannappa *et al.*, 2014; Rahmathulla *et al.*, 2019) [30, 26]. Concurrent advances in formulation technologies such as liquid biofertilizers, carrier-based granules, encapsulated inoculants, and biochar or compost enriched formulations have further improved microbial survival, shelf life, and field performance across diverse agro-climatic conditions (Bhattacharya *et al.*, 2020; Singh *et al.*, 2023) [5, 33]. Recent reviews emphasize that

microbial consortia integrated with innovative formulations offer greater functional stability under climate stress, reduce reliance on chemical fertilizers, and ensure more consistent productivity responses than conventional bioinputs (Kumar *et al.*, 2024b; Pandey & Saharan, 2025; Amit Kaur *et al.*, 2025) [23, 25, 2]. Collectively, accumulated evidence establishes microbial consortia and advanced formulations as next-generation biological inputs with strong potential to support sustainable and climate-smart sericulture systems.

Mechanisms of action

Nutrient mobilization and leaf quality

Nutrient mobilization is a central mechanism regulating mulberry leaf yield and quality, with direct consequences for silkworm growth, survivability, and cocoon productivity. Earlier studies have shown that biological inputs enhance nutrient availability and uptake through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and improved root-soil interactions (Sengupta *et al.*, 2000; Dandin *et al.*, 2003a) [31, 9]. Biofertilizers such as *Azotobacter* and *Azospirillum* improve nitrogen nutrition and leaf protein content, while phosphate- and potassium-solubilizing microorganisms increase P and K availability via organic acid production and enzymatic mineralization (Gyaneshwar *et al.* 2002, Datta, 2005b; Ghosh *et al.*, 2010) [19, 13, 15]. Arbuscular mycorrhizal fungi further strengthen nutrient mobilization by expanding effective root surface area and facilitating uptake of relatively immobile nutrients, particularly phosphorus and micronutrients, resulting in improved chlorophyll content and leaf succulence (Govindan *et al.*, 2007a; Hariprasad & Niranjana, 2009a) [16, 20]. Organic amendments, including farmyard manure, vermicompost, composted sericulture wastes, and mulberry litter residues, enhance soil organic carbon, cation exchange capacity, microbial biomass, and enzymatic activity, thereby improving nutrient retention and gradual, crop-synchronized nutrient release (Saha *et al.*, 2008; Bhattacharya *et al.*, 2010) [28, 4]. Integrated nutrient management combining biofertilizers with organic amendments consistently results in higher mulberry leaf yield, improved macro and secondary nutrient content, and superior leaf biochemical attributes such as crude protein, moisture, and reduced fiber compared with sole chemical fertilization (Bongale *et al.*, 2004, Sudharkar *et al.*, 2006; Rahmathulla *et al.*, 2019) [6, 26]. Recent reviews further confirm that microbial consortia and liquid biofertilizer formulations stabilize nutrient mobilization under variable climatic conditions, sustaining leaf nutritional quality critical for efficient silkworm feeding and cocoon quality (Bhattacharya *et al.*, 2020; Ahammed, 2025) [5, 1]. Collectively, evidence underscores biologically mediated nutrient mobilization as a key driver of sustainable mulberry productivity and sericulture performance.

Soil physical properties, moisture buffering and carbon dynamics

Improvement of soil physical properties, enhanced moisture buffering capacity, and favorable carbon dynamics are among the most critical ecosystem level benefits derived from the application of biofertilizers and organic amendments in mulberry cultivation. Early studies demonstrated that continuous use of organic manures and composts improves soil structure, reduces bulk density, and increases porosity and aggregate stability, thereby facilitating better root proliferation and nutrient uptake in mulberry plantations (Sengupta *et al.*, 2000; Lal, 2006) [31, 24]. Organic amendments such as farmyard manure, vermicompost, composted sericulture wastes, mulberry litter

residues, and press-mud contribute to the formation of stable soil aggregates through enhanced microbial activity and organic binding agents, leading to improved soil aeration and infiltration rates (Datta, 2005b; Ramesh *et al.*, 2012) [13, 27]. Improved soil structure directly enhances moisture retention and buffering capacity, which is particularly important in rainfed and drought-prone sericulture regions, as it moderates soil temperature fluctuations and sustains mulberry growth during intermittent dry spells (Govindan *et al.*, 2007b; Thangavelu *et al.*, 2016) [17, 36]. Biofertilizers and microbial consortia further reinforce these effects by stimulating microbial polysaccharide production and hyphal networks, especially through arbuscular mycorrhizal fungi, which improve soil aggregation and water-holding capacity (Kumar *et al.*, 2024a; Hariprasad & Niranjana, 2009) [22, 20]. From a carbon dynamics perspective, long-term application of organic amendments has been shown to significantly increase soil organic carbon (SOC) pools, enhance carbon stabilization within micro-aggregates, and reduce carbon losses through mineralization, thereby contributing to soil fertility restoration and climate change mitigation (Bongale *et al.*, 2004, Sudharkar *et al.*, 2006) [6, 1]. Emerging role of biochar and compost-biofertilizer combinations in enhancing carbon sequestration, improving moisture-use efficiency, and sustaining mulberry productivity under variable climatic conditions (Singh & Cowie 2014; Singh *et al.*, 2023) [32, 33]. Current literature highlights the need for long term, system based evaluations to quantify carbon sequestration potential and moisture resilience across different mulberry growing agro ecological zones. Accumulated evidence establishes soil physical improvement, moisture buffering, and positive carbon dynamics as central mechanisms through which biological inputs contribute to sustainable and climate-smart sericulture.

Plant physiological modulation and stress tolerance

Improvement of soil physical properties, enhanced moisture buffering, and favorable carbon dynamics represent key ecosystem-level benefits of biofertilizers and organic amendments in mulberry cultivation. Organic amendments such as farmyard manure, vermicompost, composted sericulture wastes, mulberry litter residues, and press-mud promote the formation of stable soil aggregates through enhanced microbial activity and organic binding agents, leading to improved soil aeration and infiltration rates (Datta, 2005b; Ramesh *et al.*, 2012) [13, 27]. Improved soil structure directly enhances moisture retention and buffering capacity, which is particularly critical in rainfed and drought-prone sericulture regions, as it moderates soil temperature fluctuations and sustains mulberry growth during intermittent dry spells (Govindan *et al.*, 2007b; Thangavelu *et al.*, 2016) [17, 36]. Biofertilizers and microbial consortia further reinforce these benefits by stimulating microbial polysaccharide production and hyphal networks, especially through arbuscular mycorrhizal fungi, thereby improving soil aggregation and water-holding capacity (Hariprasad & Niranjana, 2009a) [20]. From a carbon dynamics perspective, long-term use of organic amendments significantly increases soil organic carbon pools, enhances carbon stabilization within soil micro-aggregates, and reduces carbon losses through mineralization, contributing to soil fertility restoration and climate change mitigation (Ramesh *et al.*, 2012; Bhattacharya *et al.*, 2020) [27, 5]. Emerging evidence highlights the role of biochar- and compost-biofertilizer-based combinations in enhancing carbon sequestration, improving moisture-use efficiency, and sustaining mulberry productivity under variable climatic conditions (Singh *et al.*, 2023; Borah *et al.*, 2023) [32, 33].

et al., 2025b) [33, 8]. Overall, accumulated evidence establishes improvements in soil physical properties, moisture buffering capacity, and carbon dynamics as central mechanisms through which biological inputs support sustainable and climate-smart sericulture, while underscoring the need for long-term, system-based evaluations across diverse agro-ecological zones.

Pest suppression and induced resistance

Biological inputs play a dual role in mulberry-based sericulture by directly suppressing pest populations and indirectly strengthening plant-induced resistance mechanisms. Early studies documented that biofertilizers, organic amendments, and beneficial microbes reduce the incidence of major mulberry pests—including leaf webbers, thrips, mites, and soil-borne insects—by improving plant vigor and modifying plant–insect interactions (Sengupta *et al.*, 2000; Datta, 2005a) [31, 12]. Mulberry plants grown under biologically managed soils exhibit thicker cuticles, enhanced leaf toughness, and balanced nutrient profiles, which collectively reduce pest feeding efficiency and population buildup (Dandin *et al.*, 2003a; Govindan *et al.*, 2007a) [9, 16]. In addition to these indirect effects, biological control agents such as *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Verticillium lecanii* have been extensively evaluated for eco-friendly pest management, providing effective suppression while maintaining leaf safety for silkworm feeding (Hariprasad & Niranjana, 2009b; Thangavelu *et al.*, 2016) [21, 36]. Beneficial microbial inoculants also trigger induced systemic resistance (ISR) by activating jasmonic acid-, ethylene-, and salicylic acid-mediated defense pathways, leading to enhanced expression of pathogenesis-related proteins, phenolics, and defensive enzymes (Govindan *et al.*, 2007a; Bhattacharya *et al.*, 2020) [16, 5]. Recent emphasis on microbial consortia and liquid biopesticide formulations highlights their broader-spectrum activity, improved field persistence, and compatibility with integrated pest management strategies (Rahmathulla *et al.*, 2019) [26]. Collectively, biologically mediated pest suppression and induced resistance reduce pesticide dependence, minimize residue risks to silkworms, and enhance resilience under climate-induced pest pressure (Singh *et al.*, 2023; Borah *et al.*, 2025a) [33, 7]. Nevertheless, variability in field performance due to environmental conditions, formulation stability, and application timing underscores the need for region-specific validation and long-term studies linking pest suppression mechanisms with silkworm productivity.

Evidence for climate-smart outcomes and economic viability

Adoption of biological inputs in mulberry-based sericulture has consistently demonstrated tangible benefits in climate resilience, productivity stability, and economic returns. Over the past two decades, studies have shown that biofertilizers, organic amendments, and microbial consortia enhance mulberry growth and leaf yield under variable environmental conditions, including erratic rainfall, elevated temperatures, and drought-prone situations (Sengupta *et al.*, 2000; Govindan *et al.*, 2007b) [31, 17]. These inputs improve nutrient use efficiency, soil moisture retention, carbon sequestration, and plant stress tolerance, collectively supporting climate-smart outcomes and reducing vulnerability to abiotic stresses (Ramesh *et al.*, 2012; Bhattacharya *et al.*, 2020) [27, 5]. Biopesticides and biological control agents further strengthen system resilience by suppressing pests without chemical residues, thereby minimizing ecological risks associated with conventional pesticide use (Dandin *et al.*, 2003c; Rahmathulla *et al.*, 2019) [11, 26]. Integrated nutrient and pest management strategies based on

biological inputs have been reported to increase cocoon yield, reduce defective cocoon percentage, and enhance silkworm survival, resulting in higher net returns and favorable benefit:cost ratios (Sannappa *et al.*, 2014; Sakthivel *et al.* 2012) [30, 29]. Recent large-scale farmer demonstrations indicate that biologically managed systems achieve 7–15% higher cocoon yield per 100 DFLs and 15–30% reductions in chemical input costs, underscoring their economic viability (Borah *et al.*, 2025b; Ahammed, 2025) [8, 1]. In addition to productivity gains, these practices enhance ecosystem services through increased soil organic carbon, improved biodiversity, and reduced greenhouse gas emissions. Overall, accumulated evidence confirms that biologically based, integrated sericulture practices provide a robust pathway toward climate-smart, sustainable, and economically profitable mulberry cultivation.

Challenges and knowledge gaps

Variability in field efficacy remains a major constraint, largely driven by soil type, temperature, moisture regimes, and seasonal fluctuations that influence microbial survival, colonization, and functional activity. Inadequate quality assurance and standardization of biofertilizer and biopesticide products further contribute to inconsistent on-farm performance across regions. Evidence from long-term, multi-location studies is limited, particularly regarding interactions between introduced microbial consortia and native soil microbiota, as well as cumulative effects on soil carbon dynamics and ecosystem services. Mechanistic understanding of induced systemic resistance, plant microbe pest interactions, and mulberry stress physiology under combined abiotic and biotic stresses also remains incomplete. In addition, socio-economic constraints including limited farmer awareness, training gaps, absence of region-specific guidelines, and initial investment costs impede large scale adoption. Integration of emerging technologies such as liquid microbial formulations, biochar enriched amendments, and precision application methods in smallholder sericulture systems are still at a nascent stage. Addressing these gaps through long-term field validation, formulation optimization, mechanistic research, and participatory, socio-economically informed extension approaches is essential for developing robust, climate-smart, and economically viable sericulture systems.

Recommendations and future research priorities

To fully realize the potential of biological inputs in sustainable and climate-smart sericulture, targeted research and development priorities are required. Long term, multi-location field trials should validate the performance of biofertilizers, microbial consortia, biopesticides, and organic amendments across diverse agro climatic conditions and soil types to generate region-specific recommendations. Strengthening quality assurance and standardization covering microbial viability, shelf life, and field efficacy is essential to ensure consistent and reliable outcomes. Mechanistic studies on plant microbe pest interactions induced systemic resistance, stress physiology, and soil carbon dynamics are needed to clarify functional pathways in mulberry ecosystems. Adoption of emerging technologies, including liquid microbial consortia, biochar-enriched formulations, nanocarriers, and precision application methods, can enhance field adaptability under climate variability. Participatory, farmer-oriented extension approaches are critical to improve awareness and adoption. Concurrently, socio-economic and policy analyses should evaluate cost benefit trade-offs and incentives to enable scaling. Interdisciplinary research integrating biological, agronomic, and socio-economic

dimensions will support development of resilient, productive, and climate-smart sericulture systems.

Conclusion

Cumulative evidence reveals that biological inputs including biofertilizers, organic amendments, microbial consortia, and biopesticides provide synergistic benefits for sustainable and climate-smart sericulture. These inputs improve soil physical and chemical properties, enhance nutrient mobilization and leaf quality, modulate plant physiology, strengthen stress tolerance, suppress pests, and induce systemic resistance, thereby supporting stable cocoon yield and quality. Farmer-participatory trials and multi-location demonstrations confirm that biologically managed systems are economically viable, environmentally sustainable, and adaptable to variable agro-climatic conditions. Despite these advances, challenges persist, including variability in field efficacy, quality standardization issues, limited mechanistic understanding, and socio-economic adoption barriers. Addressing these gaps through long-term field validation, mechanistic studies, formulation optimization, participatory extension, and policy support is essential for scaling biologically based practices. Integrated research spanning soil science, plant physiology, microbiology, pest management, and socio-economics will enable development of resilient, profitable, and climate-adaptive sericulture systems.

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