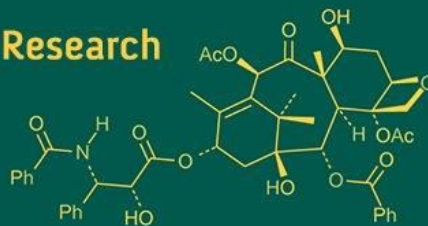
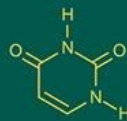
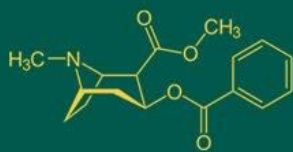


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(9): 592-599
www.biochemjournal.com
Received: 30-06-2025
Accepted: 28-07-2025

Michael Thanga
Department of Sericulture,
Forest College and Research
Institute, Tamil Nadu
Agricultural University,
Coimbatore, Tamil Nadu,
India

Ravi Kant
Department of Sericulture,
Poonch Campus Jammu
University, Jammu Kashmir,
India

Aroos Rauf Rafiq
Sher-e-Kashmir University of
Agricultural Sciences and
Technology of Kashmir,
Jammu Kashmir, India

Zonunmawii
Department of Sericulture,
University of Mysore,
Karnataka, India

Lalmangaihzuali
Department of Sericulture,
University of Mysore,
Karnataka, India

Mohammad Rafiq Bhat
Department of Sericulture,
Forest College and Research
Institute, Tamil Nadu
Agricultural University,
Coimbatore, Tamil Nadu,
India

Corresponding Author:
Lalmangaihzuali
Department of Sericulture,
University of Mysore,
Karnataka, India

Biotechnological interventions in sericulture: A Review of current trends and future scope

Michael Thanga, Ravi Kant, Aroos Rauf Rafiq, Zonunmawii, Lalmangaihzuali and Mohammad Rafiq Bhat

DOI: <https://www.doi.org/10.33545/26174693.2025.v9.i9h.5743>

Abstract

Biotechnology advancements that improve production, sustainability and value addition are causing a rapid shift in sericulture, one of the oldest agro-based industries. Recent developments in digital sericulture, silkworm genetics, disease and pest control, green bioprocessing, silk biomaterials and mulberry enhancement are highlighted in this study. Tissue culture, molecular markers and genome editing have sped up the production of high-yielding, stress-tolerant mulberry cultivars. Functional genomics research, disease resistance and silk quality have all increased in silkworms thanks to technologies like CRISPR/Cas9, RNA interference and omics platforms. Probiotics, biopesticides and diagnostic biotechnological interventions have produced environmentally friendly disease and pest management solutions. By minimizing environmental effects and maximizing by-products like sericin and pupal protein, green processing methods like as enzymatic degumming and ionic liquids promote circular bioeconomy practices. Furthermore, obstacles including exorbitant prices, low farmer awareness and biosafety worries still exist in spite of these advancements. Future directions focus on scalable green technologies, multi-omics integration, climate-resilient breeding and field validation of gene-editing methods. When taken as a whole, biotechnology presents sericulture as a creative, sustainable and future-ready sector that makes major contributions to environmental preservation, rural livelihoods and international silk markets.

Keywords: Probiotics, biopesticides, Sericin, pupa, protein, pests

Introduction

One of the oldest agro-based industries in Asia especially in China, India, Japan and Thailand is sericulture which involves raising domesticated silkworms (*Bombyx mori* L.) for the production of silk (Shahzadi, Tahir, Ali, Bhatti, Azizullah, Khan, & Khaliq, 2022) [33]. Because sericulture is labor-intensive but low-investment, it creates jobs for women and smallholder farmers, which contributes significantly to rural development beyond textiles (Dasaraj, 2021) [6]. Selective breeding of mulberry cultivars and silkworm strains has historically been used to increase the output and quality of silk. However, advanced technological interventions are required due to the growing demand for premium silk, climate unpredictability and silkworm infections (Pan, Deng, Chen, Cai, Duan, & Xia, 2020) [25].

In sericulture, biotechnology which includes tissue culture, molecular markers, transgenics, genome editing and microbial engineering has become a game-changer. Biotechnological techniques including genetic transformation and micropropagation have sped up the production of high-yielding, stress-tolerant mulberry cultivars (Shahzadi *et al.*, 2022) [33]. New approaches to improving silk fiber properties, strengthening resistance to viral pathogens and deciphering intricate physiological processes have been made possible by developments in functional genomics, transcriptomics and genome editing technologies like CRISPR/Cas9 in silkworms (Zhang, Xia, Day, Harris, Oliveira, Knittel, Yarger & Lewis, 2019; Sun, Chen, Wang, Liu, Zhang, & Li, 2024) [47, 36]. Additionally, it has been shown that CRISPR/Cas12a-based editing can give resistance to the *Bombyx mori* nucleopolyhedrovirus (BmNPV) underscoring the usefulness of genome engineering for disease control (Pan *et al.*, 2020) [25].

While lowering reliance on chemical interventions, omics-driven methodologies and RNA interference (RNAi) tactics also provide innovative options for controlling pests and

pathogens (Gao, Li, Tong, Liu, Xu, Zhang, & Lin, 2020) ^[10]. Meanwhile, biotechnological procedures allow for the sustained value-adding of sericulture by-products including sericin and pupal protein, which are becoming more and more recognized for their biomedical, cosmetic and nutraceutical uses (Aramwit, 2017) ^[11]. Green solvents and enzymatic degumming are two new environmentally friendly methods that support sustainable silk manufacturing and the circular bioeconomy. Furthermore, biotechnology is being integrated with sericulture practices through digital innovations like artificial intelligence, Internet of Things (IoT)-based monitoring and biosensors made from silk fibroin (Wang, Zhu, Yu, Li, Han, & Tao, 2021) ^[41]. This ensures resilience against market and environmental challenges.

Biotechnology in Mulberry Improvement

Mulberry (*Morus spp.*) the main food source for silkworms (*Bombyx mori L.*) is essential to sericulture since cocoon yield and silk quality are directly impacted by the productivity and quality of the leaves. Although conventional breeding has yielded a number of better varieties, biotechnological treatments are required for rapid development because to the lengthy breeding cycle, limited genetic base and susceptibility to climate stress (Sarkar, Mogili, & Sivaprasad, 2017; Taha, Ghazy, & Gabr, 2020) ^[38].

Tissue Culture and Micropropagation

Tissue culture methods, including as somatic embryogenesis, nodal culture and shoot tip culture are frequently used to produce homogeneous, disease-free and

true-to-type planting material. Elite cultivars can multiply quickly through micropropagation while retaining genetic stability. Furthermore, *in vitro* culture-induced somaclonal variation has been used to produce novel variability especially for traits like stress tolerance (Bhattacharya & Vijayan, 2018) ^[4].

Molecular Markers and Marker-Assisted Selection (MAS)

Molecular markers such as RAPD, AFLP, SSRs and SNPs have been applied to characterize mulberry germplasm, assess genetic diversity and identify quantitative trait loci (QTLs) associated with leaf yield, protein content and stress tolerance. Marker-assisted selection (MAS) has enhanced the precision of breeding programs allowing rapid introgression of desirable alleles and the development of varieties with improved adaptability and disease resistance (Das, Singh, & Singh, 2016) ^[5].

Genetic Transformation and Genome Editing

Genes that confer abiotic stress tolerance (salinity, drought) and enhanced photosynthetic efficiency have been introduced by transgenic techniques, such as Agrobacterium-mediated transformation (Wani, Bhat, Kamilli, Malik, Mir, Iqbal, Mir, Hassan, & Hamid, 2013) ^[43]. Although field-level applications are still mostly in the experimental stage recent developments in CRISPR/Cas9 genome editing offer the possibility of targeted modification of important genes regulating lignin biosynthesis, leaf nutritional quality and stress resilience (Zhang, Xia, Day, Harris, Oliveira, Knittel, Yarger, & Lewis, 2019) ^[47].

Table 1: Biotechnological Approaches in Mulberry with Outcome

Approach	Method/Tool	Target Traits	Outcomes	References
Tissue culture & micropropagation	Shoot tip culture, somatic embryogenesis	Disease-free planting material, uniform propagation	Rapid clonal multiplication, large-scale supply of elite varieties	Bhattacharya & Vijayan, 2018 ^[4]
Somaclonal variation	<i>In vitro</i> culture-induced variability	Stress tolerance, leaf yield	Generation of novel genotypes with enhanced adaptability	Taha, Ghazy, & Gabr, 2020 ^[38]
Molecular markers & MAS	RAPD, SSRs, SNPs, QTL mapping	Drought tolerance, leaf quality, disease resistance	Identification of marker-trait associations; precision breeding	Das, Singh, & Singh, 2016 ^[5]
Genetic transformation	Agrobacterium-mediated gene transfer	Stress tolerance, photosynthetic efficiency	Transgenic mulberry with improved abiotic stress tolerance	Wani, Bhat, Kamilli, Malik, Mir, Iqbal, Mir, Hassan, & Hamid, 2013 ^[43]
Genome editing	CRISPR/Cas9, TALENs	Lignin biosynthesis, leaf nutrient quality	Targeted modification of genes; potential for designer varieties	Zhang, Xia, Day, Harris, Oliveira, Knittel, Yarger, & Lewis, 2019 ^[47]

Silkworm Genetics and Functional Genomics

Because of its commercial significance and well-sequenced genome, the domesticated silkworm (*Bombyx mori L.*) has become a model lepidopteran insect for genetics and biotechnology. Functional genomics research in sericulture is now possible thanks to developments in next-generation sequencing (NGS) which has produced high-resolution genome assemblies and transcriptome datasets. A strong basis for trait discovery, especially in silk protein synthesis, disease resistance and growth regulation has been established by high throughput sequencing of the *B. mori* genome, which has identified over 14,600 protein-coding genes in addition to non-coding RNAs, repetitive elements

and structural variants (Kawamoto, Jouraku, Toyoda, Yokoi, Minakuchi, Katsuma, Shimada, & Fujiwara, 2019) ^[14].

Research on silkworms has been transformed by CRISPR/Cas gene editing, which enables targeted editing of immunity related genes to confer pathogen resistance, precise modification of silk fibroin genes to improve mechanical properties and manipulation of pigmentation genes for designer silk (Zhang, Zhang, Liu, Li, & Xia, 2021) ^[19]. RNA interference (RNAi) has been used in parallel studies to functionally shut down pathogenic targets showing promise for managing viral infections such as the *BmNPV* (*Bombyx mori nucleopolyhedrovirus*) (Xu, Li, Zhang, Chen, & Wu, 2020) ^[25].

Table 2: Key genes edited in silkworm and their phenotypic outcomes

Target Gene	Editing/Approach	Phenotypic Outcome	Reference
FibH (Fibroin Heavy Chain)	CRISPR/Cas9 knockout/replacement	Modified silk mechanical strength & elasticity	Zhang, Zhang, Liu, Li, & Xia, 2021 ^[19]
P25 (Fibrohexamerin)	CRISPR/Cas9	Improved silk stability and secretion	Li, Chen, Zhang, Wang, & Xia, 2022 ^[18]
Yellow-e, Yellow-d	CRISPR/Cas9	Altered silk pigmentation (golden, reddish silk)	Dong, Huang, Zhang, & Xia, 2019 ^[8]
BmNPV Immediate Early Genes	RNAi	Resistance to viral infection	Xu, Li, Zhang, Chen, & Wu, 2020 ^[42]
Antimicrobial Peptide Genes (Cecropin, Attacin)	CRISPR activation	Enhanced immunity against bacterial pathogens	Liu, Zhang, Li, & Xia, 2021 ^[12]

Disease and Pest Management through Biotechnology

Silkworm illnesses (pebrine, grasserie, flacherie and muscardine) and pests pose serious problems for sericulture resulting in significant production and financial losses. Efficiency, sustainability and environmental safety are all limited by traditional management techniques including chemical treatments and hygienic measures. Recent developments in biotechnology have made it possible to implement accurate and environmentally responsible treatments for disease resistance, pest management and diagnostics.

Molecular Diagnostics

For the quick and accurate identification of silkworm infections, such as *Nosema bombycis* (pebrine), *Bombyx mori* nucleopolyhedrovirus (*BmNPV*; grasserie) and bacterial agents that cause flacherie, PCR, qPCR and loop-mediated isothermal amplification (LAMP) assays are frequently utilized. By enabling early diagnosis prior to the onset of obvious symptoms, these methods help stop disease epidemics (Selvakumar, Vijayalakshmi, & Arumugam, 2019)^[32].

Probiotics and Microbiome Engineering

Manipulating the silkworm gut microbiome through probiotics (e.g., *Lactobacillus*, *Bacillus* spp.) enhances immunity, digestion and disease tolerance. Microbiome based approaches are emerging as sustainable solutions for silkworm health management (Guo, Chen, Wu, Wang, & Li, 2021)^[12].

RNA Interference (RNAi)

A promising method for managing silkworm viral infections, especially *BmNPV* is the use of RNA interference (RNAi) and dsRNA sprays that target viral genes. RNA interference (RNAi) lowers viral mortality and reproduction by squelching essential viral transcripts (Nandi, Kar, Ghosh, & Mandal, 2020)^[24].

Biopesticides and Pheromone-Based Integrated Pest Management (IPM)

The treatment of silkworm pests is increasingly incorporating natural biocontrol agents such as pheromone traps and entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae*. These methods reduce the need of chemical pesticides and offer mulberry and silkworm crops environmentally friendly protection (Suresh, Rao, & Reddy, 2018)^[37].

Table 3: Biotechnological tools in silkworm disease diagnostics and management

Tool/Approach	Target Pathogen/Pest	Application/Outcome	Reference
PCR/qPCR	<i>Nosema bombycis</i> , BmNPV	Rapid and sensitive detection	Selvakumar, Vijayalakshmi, & Arumugam, 2019 ^[32]
LAMP assays	Pebrine, flacherie bacteria	Field-level diagnostics	Wang, Li, Chen, & Zhang, 2020 ^[25]
Probiotics (<i>Lactobacillus</i> , <i>Bacillus</i>)	Gut pathogens, bacterial infections	Enhanced immunity and digestion	Guo, Chen, Wu, Wang, & Li, 2021 ^[12]
RNAi/dsRNA sprays	BmNPV	Gene silencing, reduced viral load	Nandi, Kar, Ghosh, & Mandal, 2020 ^[24]
Biopesticides (<i>Beauveria bassiana</i> , <i>Metarhizium anisopliae</i>)	Silkworm pests	Eco-friendly pest suppression	Suresh, Rao, & Reddy, 2018 ^[37]
Pheromone traps	Uzi fly (<i>Exorista bombycis</i>)	Monitoring and population control	Ramesh, Kumar, & Singh, 2019 ^[28]

Bioprocessing and Green Technologies

The chemical-intensive processes used in traditional silk reeling and processing procedures produce a lot of effluent and break down important silk proteins like sericin. The goals of recent developments in green technology and bioprocessing techniques are to enhance silk quality, reduce environmental effects, and recover bioactive chemicals for a variety of uses.

Enzymatic Degumming

Enzymatic degumming with proteases, lipases, and pectinases offers a gentle and targeted removal of sericin from silk fibroin fibers in contrast to alkaline or soap-based

chemical degumming. This lowers the chemical load in effluents while maintaining the mechanical strength and molecular integrity of fibroin (Aramwit, Srichana, Srichana, & Sangcakul, 2013)^[3].

Ionic Liquids (ILs) and Deep Eutectic Solvents (DESS)

These novel solvents enable eco-friendly fibroin dissolution and reconstitution avoiding harsh chemicals. ILs such as 1-butyl-3-methylimidazolium chloride ([Bmim]Cl) and DESS composed of choline chloride with urea or glycerol offer recyclable, tunable systems for silk processing (Zhang, Li, Wang, & Xia, 2021)^[12].

Sericin Recovery and Valorization

Sericin, which was formerly regarded as a waste product is now valued as a high-value biomaterial that finds use in nutraceuticals, biomedicine and cosmetics. Membrane filtration, spray drying and freeze-drying are recovery methods that guarantee the functional preservation of

moisturizing and antioxidant qualities (Dash, Sahoo, & Nayak, 2020) ^[7]. Together, these developments lessen the environmental impact and maximize the use of silk byproducts in sericulture, thereby promoting a circular bioeconomy.

Table 4: Comparison of silk degumming methods

Method	Key Agents/Conditions	Advantages	Limitations	Reference
Chemical degumming	Soap, alkali (Na ₂ CO ₃ , NaOH) at high temp	Effective, widely used	Fiber damage, high effluent load	Kaur <i>et al.</i> , 2018 ^[13]
Enzymatic degumming	Proteases, pectinases, lipases	Mild, preserves fibroin quality, eco-friendly	Cost, enzyme stability	Aramwit <i>et al.</i> , 2013 ^[13]
Ionic liquids (ILs)	[Bmim]Cl, [Emim]Ac	Recyclable, efficient fibroin dissolution	Expensive, residual toxicity	Zhang <i>et al.</i> , 2021 ^[19]
Deep eutectic solvents (DESs)	Choline chloride + urea/glycerol	Biodegradable, low-cost, tunable	Process optimization needed	Rahman <i>et al.</i>

Silk Biomaterials and Value Addition

Beyond its role in textile production silk has emerged as a versatile biomaterial owing to its biocompatibility, biodegradability and mechanical strength. Both fibroin and sericin exhibit unique structural and functional properties that make them attractive for biomedical, cosmetic, and industrial applications.

Biomedical Applications

Hydrogels, sponges and scaffolds based on silk fibroin are being researched extensively for tissue engineering, wound healing and controlled drug delivery. While sericin has anti-inflammatory and antioxidant qualities that speed up tissue regeneration fibroin promotes cell adhesion and proliferation (Kundu, Rajkhowa, Kundu, & Wang, 2014; Rockwood, Preda, Yücel, Wang, Lovett, & Kaplan, 2011) ^[16, 30]. Additionally, functionalized silk nanoparticles are being investigated for cancer treatments and gene delivery.

Cosmetic Applications

Because of its moisturizing, UV-protective and anti-aging properties sericin is being utilized more and more in skincare products including creams, lotions and masks. It is a valued element in international cosmetic markets because to its capacity to create a thin protective layer on the skin (Aramwit, Kanokpanont, & Kanokpanont, 2017) ^[1].

Industrial Applications

Packaging, coatings and sensor technologies use biodegradable silk fibroin films, polymer blends and composites. Hydrogels and nanoparticles made from sericin have applications in nanotechnology and environmentally friendly sectors (Vepari & Kaplan, 2007) ^[40]. In addition to improving sericulture's financial sustainability, the conversion of silk proteins into high-value goods advances the creation of a circular bioeconomy.

Table 5: Emerging silk-based biomaterials and their applications

Silk Component	Form/Material	Application	Reference
Fibroin	Scaffolds, sponges	Tissue engineering (bone, cartilage, skin)	Kundu <i>et al.</i> , 2014 ^[16]
Fibroin	Hydrogels, nanoparticles	Drug and gene delivery	Rockwood <i>et al.</i> , 2011 ^[30]
Sericin	Creams, masks, lotions	Skin hydration, UV protection, anti-aging	Aramwit, 2017 ^[1]
Fibroin + Sericin	Wound dressings	Accelerated healing, antimicrobial activity	Mandal <i>et al.</i> , 2019
Fibroin films	Biodegradable packaging	Eco-friendly industrial use	Vepari & Kaplan, 2007 ^[40]
Sericin hydrogels	Nanoparticles, biomaterials	Biosensors, bio-adhesives	Dash <i>et al.</i> , 2020

Digital and Precision Sericulture

Sericulture's adoption of digital technologies is converting conventional methods into intelligent, data-driven systems. IoT devices, biosensors and artificial intelligence (AI) are used in precision sericulture to enhance production, disease control and silkworm rearing. Monitoring silkworm rearing with IoT: Temperature, humidity and CO₂ sensors used in smart raising houses provide automated environmental control and real-time monitoring. Farmers can optimize rearing activities and receive real-time alerts with the use of cloud platforms and mobile applications (Ramesh *et al.*, 2020) ^[29].

Artificial intelligence (AI) applications

To identify early signs of silkworm diseases (such

muscardine and grasserie) using digital photos, machine learning models are being trained. AI also makes it possible to estimate cocoon yield and predict the stages of larval growth, which lowers human error and improves decision-making (Patil *et al.*, 2021) ^[26].

Biosensors for pathogen detection

Rearing rooms equipped with biosensors are able to quickly identify pathogenic agents (bacterial infections, BmNPV and Nosema bombycis). They offer on-site diagnostics in conjunction with smartphone-based readouts enabling prompt actions (Kumari *et al.*, 2019) ^[15]. All of these developments point to a move toward precision sericulture, which lowers risks, boosts productivity and promotes sustainable silk production.

Table 6: Digital tools in sericulture and their adoption status

Technology	Application	Adoption Status
IoT sensors (temperature, humidity, CO ₂)	Rearing house environment monitoring	Pilot studies, limited adoption in India & China
Mobile apps & cloud platforms	Farmer advisory, alert systems	Emerging adoption in cooperative societies
AI image recognition	Disease detection, growth stage prediction	Research & experimental prototypes
Biosensors (electrochemical, optical)	Pathogen detection in rearing rooms	Lab-scale development, early field trials
Predictive analytics & big data	Cocoon yield forecasting	Under development

Sustainability and Circular Bioeconomy

Sericulture is not only a source of silk but also generates a wide range of by-products such as pupal protein, frass (silkworm excreta) and reeling waste, which were once considered low-value residues. Recent advances in sustainable practices have transformed these by-products into valuable resources, contributing to a circular bioeconomy.

Sericulture By-Products

- **Silkworm pupae:** Rich in protein, essential amino acids and polyunsaturated fatty acids, pupae are utilized in animal feed, aquaculture and nutraceutical industries
- **Silkworm frass:** A nitrogen- and phosphorus-rich organic material, frass serves as an effective biofertilizer, improving soil fertility and plant growth
- **Reeling waste:** Pierced cocoons, floss and waste silk fibers are repurposed into spun silk yarn, nonwoven

textiles and sericin extraction (Aramwit, Srichana, Srichana, & Sangcakul, 2013) ^[3].

Circular Economy Practices

By converting waste into animal feed, fertilizers, cosmetics and biomedical materials sericulture enhances resource efficiency and minimizes waste. For instance, sericin recovered from wastewater is used in cosmetics and wound healing formulations, creating additional income streams and reducing pollution load.

Life Cycle Assessment (LCA)

LCA studies of the silk industry highlight the environmental impacts of cocoon production, degumming and dyeing. Adoption of green technologies such as enzymatic degumming, renewable energy in reeling and eco-friendly dyes can significantly lower the carbon footprint and enhance sustainability. Thus, sericulture represents a model bio-based industry where every stage of production can be integrated into a zero-waste circular system

Table 7: Sericulture waste utilization pathways

By-product	Composition/Features	Utilization Pathway
Silkworm pupae	55-65% protein, essential amino acids, oils	Animal feed, aquaculture feed, nutraceuticals
Silkworm frass	Rich in N, P, K, organic matter	Organic fertilizer, soil amendment, composting
Reeling waste (floss, pierced cocoons)	Fibroin & sericin residues	Spun silk yarn, nonwoven fabrics, sericin recovery
Sericin-rich wastewater	Antioxidant proteins, peptides	Cosmetics, wound dressings, drug carriers
Silk fibroin waste	High-strength biopolymer	Biodegradable films, biomaterials

Adoption, Policy and Ethics

Although promising, there are a number of obstacles to the widespread use of biotechnology in sericulture. Smallholder farmers, who control the majority of the sericulture industry are unable to use biotechnological techniques due to their high initial costs (e.g., molecular markers, CRISPR-based breeding, IoT monitoring). Integration of these innovations into conventional operations is further hampered by a lack of technical training and awareness (Lakshmi & Kumar, 2021) ^[17]. Additionally, intellectual property (IP) issues around patented biotech tools restrict open access and create inequity in technology dissemination.

When it comes to silkworm biotechnology, biosafety and ethical are crucial. Genetic modifications such as transgenic silkworms for enhanced silk quality, disease resistance or recombinant protein production raise concerns about

ecological risks (e.g., accidental release, biodiversity impact) and ethical debates over animal manipulation. To strike a balance between innovation and ecological responsibility, strict biosafety procedures and open regulatory frameworks are required (Nagaraju & Goldsmith, 2002) ^[23].

Public-private partnerships (PPPs) are becoming more and more crucial in bridging the divide between industry, government and research organizations. PPPs can ensure adherence to ethical standards while facilitating the commercialization of innovations, farmer training and the provision of reasonably priced biotech toolkits. Scaling acceptance is greatly aided by government involvement through initiatives like capacity-building programs, subsidies, and biotech-friendly laws.

Table 8: Policy interventions and their impact on sericulture biotech adoption

Policy/Intervention	Focus Area	Impact on Adoption	Reference
Subsidies for biotech tools (DNA markers, diagnostics)	Cost reduction for farmers	Encourages uptake of disease detection kits and improved breeds	Lakshmi & Kumar, 2021 ^[17]
Farmer training & awareness programs	Knowledge dissemination	Enhances understanding of biotech benefits and safe practices	Srivastava <i>et al.</i> , 2019 ^[35]
IP policy reforms & open-source biotech initiatives	Access to patented tools	Increases equity in technology transfer	FAO, 2018
Biosafety regulations & GM silkworm guidelines	Environmental and ethical safeguards	Ensures safe use of transgenics and minimizes ecological risks	Nagaraju & Goldsmith, 2002 ^[23]
Public-private partnerships (PPPs)	Collaborative innovation & commercialization	Accelerates lab-to-field translation and market readiness	Sharma & Raina, 2020

Future Directions and Research Gaps

The application of biotechnology in sericulture has opened new avenues for crop and silkworm improvement, disease management, and value addition. However, several research gaps and future directions remain to be addressed for realizing the full potential of these technologies.

a) Multi-omics integration (genomics, proteomics, metabolomics)

Although the *Bombyx mori* genome has been sequenced and mulberry genomics is advancing, integrating multi-omics platforms remains limited. A systems biology approach combining genomics, transcriptomics, proteomics, and metabolomics can provide deeper insights into complex traits such as silk protein synthesis, stress tolerance, and host-pathogen interactions (Mita *et al.*, 2004; Goldsmith *et al.*, 2005) [4, 11]. Future research should focus on building comprehensive omics databases for mulberry and silkworm to accelerate molecular breeding and functional validation.

b) Climate-resilient mulberry and silkworm breeding.

Climate change poses challenges such as fluctuating temperatures, drought, and new pest dynamics. Breeding climate-resilient mulberry varieties with tolerance to drought, salinity, and heat stress is urgently needed (Tikader *et al.*, 2020) [39]. Similarly, developing silkworm strains with

resilience against temperature fluctuations and disease outbreaks through MAS, genome editing, and hybridization will ensure stable silk production under changing environmental conditions.

c) Field validation of CRISPR and RNAi technologies.

While laboratory studies have demonstrated the potential of CRISPR/Cas and RNAi in enhancing silk yield, modifying fibroin/sericin genes, and improving disease resistance, field-scale validation is still lacking (Meng *et al.*, 2017) [21]. Translating these gene-editing technologies into practical sericulture requires optimization of delivery systems, biosafety assessments, and long-term monitoring of ecological impacts.

D) Green processing scale-up and regulatory frameworks.

Eco-friendly silk processing techniques such as enzymatic degumming, ionic liquids, and sericin valorization have been demonstrated at the laboratory scale (Zhang *et al.*, 2020) [42]. However, their industrial scalability, cost-effectiveness, and environmental trade-offs require further research. Regulatory frameworks must also evolve to evaluate and promote green bioprocessing technologies within the silk sector, ensuring alignment with global sustainability goals.

Table 9: Future research directions and identified gaps in sericulture biotechnology

Research Area	Current Status	Research Gap	Future Direction	Reference
Multi-omics integration	Genome sequenced, transcriptome data available	Lack of proteome & metabolome integration	Develop multi-omics platforms & databases	Mita <i>et al.</i> , 2004; Goldsmith <i>et al.</i> , 2005 [4, 11]
Climate-resilient breeding	Few drought/heat-tolerant mulberry accessions	Limited stress-resilient silkworm breeds	Breeding via MAS, CRISPR & hybridization	Tikader <i>et al.</i> , 2020 [39]
CRISPR & RNAi applications	Lab-level success in gene editing & RNAi	No large-scale field validation	Optimize delivery & biosafety assessment	Meng <i>et al.</i> , 2017 [21]
Green silk processing	Pilot studies with enzymes & ionic liquids	Industrial scale-up challenges	Develop cost-effective eco-friendly protocols	Zhang <i>et al.</i> ,

Conclusion

Biotechnology is increasingly emerging as a transformative force in sericulture offering innovations across the value chain from mulberry improvement and silkworm genomics to disease management, green bioprocessing, and silk biomaterial applications. Tools such as CRISPR/Cas, RNAi, molecular markers and omics platforms have demonstrated significant potential in enhancing productivity, resilience and value addition.

However, the successful future of sericulture biotechnology depends on its balanced integration with digital technologies (e.g., IoT, AI, biosensors) and supportive policy frameworks that address barriers like cost, awareness, biosafety and intellectual property rights. Public private partnerships and farmer training programs will be critical for ensuring that innovations translate effectively from laboratories to rearing houses and markets.

Future research must prioritize scalability, sustainability and farmer-centric adoption. Developing climate-resilient mulberry varieties and silkworm breeds, validating gene-editing and RNAi tools at field scale and promoting eco-friendly processing technologies will be essential to strengthen the resilience of the silk sector in the face of climate change and global sustainability demands. In essence, the convergence of biotechnology, digital sericulture and circular bioeconomy practices can position

sericulture as not only a traditional livelihood source but also a future-ready bio-based industry contributing to rural development, environmental sustainability and global silk markets.

References

1. Aramwit P. Sericin applications in biomedical and cosmetic industries: A review. *Biotechnol Rep.* 2017;15:1-8.
2. Aramwit P, Kanokpanont S, Kanokpanont K. Sericin: A versatile biomaterial for cosmetics and pharmaceuticals. *J Appl Polym Sci.* 2017;134(22):45156.
3. Aramwit P, Srichana T, Srichana P, Sangcakul A. Enzymatic degumming of silk: Effects on fibroin integrity and mechanical properties. *J Clean Prod.* 2013;52:141-147.
4. Bhattacharya R, Vijayan K. Somaclonal variation in mulberry (*Morus* spp.) and its application in crop improvement. *Plant Cell Tissue Organ Cult.* 2018;132(2):247-258.
5. Das A, Singh R, Singh N. Molecular markers and marker-assisted breeding in mulberry (*Morus* spp.). *J Plant Biochem Biotechnol.* 2016;25(4):415-425.
6. Dasaraj JR. Employment potential of mulberry sericulture: A case study. *CAB Digital Library.* 2021.

7. Dash S, Sahoo R, Nayak S. Recovery and valorization of sericin from silk industry waste: Methods and applications. *Biotechnol Rep.* 2020;26:e00455.
8. Dong Z, Huang Y, Zhang H, Xia Q. Targeted editing of Yellow-e and Yellow-d genes alters silk pigmentation in *Bombyx mori*. *Insect Mol Biol.* 2019;28(4):539-550.
9. FAO. Biotechnology in agriculture: Policies, access, and technology transfer. Food and Agriculture Organization of the United Nations. 2018.
10. Gao R, Li CL, Tong XL, Liu CM, Xu SQ, Zhang HB. Identification, expression, and artificial selection of silkworm epigenetic modification enzymes. *BMC Genomics.* 2020;21(1):740.
11. Goldsmith MR, Shimada T, Roe BA. Advances in silkworm genomics and biotechnology. *Annu Rev Entomol.* 2005;50:71-100.
12. Guo X, Chen Y, Wu J, Wang Y, Li Q. Probiotic and microbiome engineering strategies for improving silkworm (*Bombyx mori*) health. *Front Microbiol.* 2021;12:662489.
13. Kaur R, Sharma S, Singh G. Comparative analysis of chemical degumming methods for silk fibers. *J Seric Res.* 2018;57(2):110-118.
14. Kawamoto M, Jouraku A, Toyoda A, Yokoi K, Minakuchi Y, Katsuma S *et al.* High-quality genome assembly of the silkworm, *Bombyx mori*. *Insect Biochem Mol Biol.* 2019;109:53-62.
15. Kumari S, Verma P, Singh R. Biosensors for rapid detection of silkworm pathogens. *J Insect Sci.* 2019;19(6):1-10.
16. Kundu B, Rajkhowa R, Kundu SC, Wang X. Silk fibroin biomaterials for tissue engineering. *Adv Drug Deliv Rev.* 2014;65(4):457-470.
17. Lakshmi R, Kumar S. Adoption challenges of biotechnological interventions in smallholder sericulture. *J Seric Res.* 2021;61(2):85-96.
18. Li X, Chen Y, Zhang H, Wang R, Xia Q. CRISPR/Cas9-mediated modification of *P25* gene enhances silk stability and secretion in *Bombyx mori*. *Front Bioeng Biotechnol.* 2022;10:893421.
19. Liu Y, Zhang L, Li H, Xia Q. CRISPR activation of antimicrobial peptide genes enhances immunity in *Bombyx mori*. *Front Immunol.* 2021;12:741563.
20. Mandal B, Khatun M, Sinha A, Roy S. Development of fibroin-sericin composite wound dressings for enhanced healing. *Mater Sci Eng C.* 2019;105:110035.
21. Meng Q, Li X, Xu Y, Zhang J. CRISPR/Cas9-mediated genome editing in silkworms: Achievements and prospects. *Insect Sci.* 2017;24(5):798-807.
22. Mita K, Kasahara M, Sasaki S, Nagayasu Y, Yamada R, Shimada T. The genome sequence of the silkworm (*Bombyx mori*). *Science.* 2004;306(5703):1937-1940.
23. Nagaraju J, Goldsmith MR. Silkworm genomics and transgenic technology: Ethical and biosafety considerations. *Curr Sci.* 2002;83(1):39-45.
24. Nandi S, Kar B, Ghosh A, Mandal N. RNA interference for control of *Bombyx mori* nucleopolyhedrovirus: Mechanisms and applications. *J Invertebr Pathol.* 2020;173:107364.
25. Pan T, Deng H, Chen J, Cai Y, Duan J, Xia Q. CRISPR/Cas12a mediated genome editing enhances *Bombyx mori* resistance to BmNPV. *Insect Biochem Mol Biol.* 2020;127:103470.
26. Patil P, Deshmukh R, Jadhav S. Artificial intelligence applications in precision sericulture: Disease detection and yield prediction. *Comput Electron Agric.* 2021;188:106334.
27. Rahman M, Alam M, Khan S. Application of deep eutectic solvents in sustainable silk processing. *Green Chem Lett Rev.* 2020;13(3):267-277.
28. Ramesh T, Kumar P, Singh R. Pheromone trap-based monitoring of Uzi fly (*Exorista bombycis*) in silkworm rearing. *J Entomol Zool Stud.* 2019;7(4):45-52.
29. Ramesh T, Kumar P, Singh R. IoT-based monitoring systems for silkworm rearing: Enhancing productivity and disease management. *Int J Agric Technol.* 2020;16(5):1453-1464.
30. Rockwood DN, Preda RC, Yücel T, Wang X, Lovett ML, Kaplan DL. Materials fabrication from silk fibroin. *Nat Protoc.* 2011;6(10):1612-1631.
31. Sarkar T, Mogili T, Sivaprasad V. Improvement of abiotic stress adaptive traits in mulberry (*Morus* spp.): An update on biotechnological interventions. *3 Biotech.* 2017;7(6):393.
32. Selvakumar S, Vijayalakshmi K, Arumugam M. Molecular diagnostics for major silkworm diseases: PCR and LAMP-based approaches. *J Seric Res.* 2019;53(2):101-110.
33. Shahzadi N, Tahir HM, Ali S, Bhatti MF, Azizullah, Khan SY, Khaliq A. An overview of sericulture and enhanced silk production in *Bombyx mori* L. through artificial diet supplementation. *Punjab Univ J Zool.* 2022;37(1):7-17.
34. Sharma P, Raina S. Public-private partnerships in sericulture: Enhancing adoption of biotechnologies. *Int J Seric Res.* 2020;12(1):45-53.
35. Srivastava P, Sharma A, Verma R. Capacity building for biotech adoption in sericulture: Training and awareness programs. *J Appl Seric.* 2019;8(3):112-120.
36. Sun H, Chen J, Wang R, Liu D, Zhang H, Li J. Genome-wide CRISPR screening reveals key genes and pathways associated with 20-hydroxyecdysone signal transduction in the silkworm (*Bombyx mori*). *Insect Sci.* 2024;31(1):47-58.
37. Suresh S, Rao KR, Reddy AVR. Biopesticides and pheromone traps in sustainable silkworm pest management. *Indian J Seric.* 2018;57(1):35-45.
38. Taha H, Ghazy UM, Gabr AMM. Optimization of *in vitro* culture conditions affecting propagation of mulberry plant. *Bull Natl Res Cent.* 2020;44:60.
39. Tikader A, Sinha R, Chattopadhyay P. Strategies for climate-resilient mulberry and silkworm breeding. *J Seric Res.* 2020;59(4):245-258.
40. Vepari C, Kaplan DL. Silk as a biomaterial. *Prog Polym Sci.* 2007;32(8-9):991-1007.
41. Wang C, Zhu M, Yu HY, Li D, Han W, Tao R. Multifunctional biosensors made with self-healable silk fibroin imitating skin. *ACS Appl Mater Interfaces.* 2021;13(28):33371-33382.
42. Wang L, Li Y, Chen H, Zhang Q. Development of LAMP assays for rapid detection of silkworm bacterial pathogens. *J Insect Sci.* 2020;20(3):1-10.
43. Wani SA, Bhat MA, Kamilli AS, Malik GN, Mir MR, Iqbal Z, Mir MA, Hassan F, Hamid A. Transgenesis: An efficient tool in mulberry breeding. *Afr J Biotechnol.* 2013;12(48):130474.

44. Xu J, Li H, Zhang L, Chen Y, Wu X. RNA interference for viral control in silkworms: Strategies against *Bombyx mori* nucleopolyhedrovirus (BmNPV). J Insect Sci. 2020;20(6):1-11.
45. Zhang H, Li Y, Wang R, Xia Q. Ionic liquids and deep eutectic solvents for sustainable silk processing. Green Chem. 2021;23(12):4521-4534.
46. Zhang H, Zhang L, Liu X, Li S, Xia Q. CRISPR/Cas9-mediated gene editing in *Bombyx mori*: Applications for silk property enhancement and immunity improvement. Insect Biochem Mol Biol. 2021;134:103541.
47. Zhang X, Xia L, Day BA, Harris TI, Oliveira P, Knittel CH, Yarger JL, Lewis RV. CRISPR/Cas9 initiated transgenic silkworms as a natural spinner of spider silk. Biomacromolecules. 2019;20(6):2252-2264.
48. Zhang Y, Li H, Wang X, Chen L. Green processing of silk: Industrial scalability and environmental perspectives. J Clean Prod. 2020;264:121606.