**Tech-Driven Sericulture: Merging Climate Resilience, Biotech and Nanotech for Sustainable Silk**

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ABSTRACT

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| Sericulture is transitioning from a traditional craft to a technology-driven industry in response to climate challenges and market demands. This review highlights recent innovations integrating biotechnology, nanotechnology, and climate-smart practices to enhance silk productivity and sustainability. Advances such as marker-assisted breeding, transgenic silkworms, and nano-fertilizers have improved mulberry growth, cocoon yield, and disease resistance. Smart rearing systems using IoT and automated tools have modernized silkworm management. Circular practices like waste recycling further support environmental goals. The review also addresses the socio-economic impact on rural communities, emphasizing the role of women and youth, while identifying adoption barriers like cost and skill gaps. These innovations collectively position sericulture for inclusive, sustainable growth in the modern era. |

*Keywords: Biotechnology, emerging technologies,* ***molecular marker, nanotechnology,*** *sericulture, silk improvement*

1. INTRODUCTION

 Sericulture, the age-old practice of silk production, plays a pivotal role in the socio-economic development of rural communities, particularly in countries like India and China. Traditionally rooted in labor-intensive processes, sericulture is undergoing a technological renaissance driven by modern challenges and opportunities. The increasing unpredictability of climate patterns, growing demand for high-quality silk, and emphasis on sustainability have necessitated a transition from conventional practices to innovative, science-based approaches.

 Recent advancements in biotechnology, nanotechnology, and smart farming have opened new horizons for enhancing silk productivity, improving cocoon quality, and ensuring ecological sustainability. Biotechnological tools such as molecular markers, transgenic techniques, and tissue culture have significantly contributed to the development of superior silkworm races and mulberry varieties (Alam*, et al.,* 2022). Simultaneously, nanotechnology has emerged as a powerful tool for improving nutrient delivery in mulberry and enhancing silkworm resilience to diseases (Dukare *et al.,*2024). Moreover, the integration of climate-resilient technologies and IoT-based rearing systems offers promising solutions to mitigate the adverse impacts of environmental stressors (Sujatha *et al*., 2024).

 This review aims to synthesize the recent technological interventions in sericulture, focusing on the integration of climate adaptation strategies, biotechnological advancements, and nanotechnological innovations to create a resilient, productive, and sustainable sericulture industry.

## ****2. IMPACT OF CLIMATE CHANGE ON SERICULTURE****

 Silkworm (Bombyx mori L.) growth and development are significantly influenced by temperature fluctuations. The ideal temperature for rearing silkworms should range between 25-26 degrees Celsius. Any variation below (20-21°C) or above (28-29°C) this range negatively impacts the growth and development of the insects (Zhang *et al.,* 2018).

 Heat shocks have been found to cause death rate rise, speed up larval stages, reduce larval weight as well as intake and utilization of silkworm food leading to low efficiency with failure in cocoon formation (Zhang, *et al.,* 2018). Moreover, abnormalities in wide-range deviations from normality may suppress silk gland activity due to inhibited synthesis process besides producing less fluid protein component used for fibers formation (Bekkamov & Samatova, 2023).

 In early stages (chawki), exposure to high temperature can inhibit subsequent phases growth towards post-cocoon parameters (Rahmathulla, 2012). Also, majority shows decreased performance if subjected to temperature or humidity fluctuation for three hours (Hussain, *et al*., 2011). The cocoon yield per box can decrease by 15–30 kilograms, with lower qualities up to 14% when optimal temperature and humidity are not maintained (Bekkamov & Samatova, 2023).

 Climate change also increases the frequency of extreme weather events like droughts, floods, and heatwaves. Temperature controls silkworm physiology as well as cocoon production. Temperatures below 20°C or above 30°C are unfavourable for the health of the silkworm (Rahmathulla, 2012). High humidity together with high temperature creates favourable environment for different kinds of diseases attacking the silkworms. Flooding caused by heavy rainfall can destroy mulberry plantations whereas drought periods adversely affect both quality and quantity of mulberry leaves (Rahmathulla, 2012).

 Sprouting behaviour in mulberry plants is shifting due to global warming: Sprouting days for mulberries have been enhanced by about 10 days (Mehraj, 2023). Mixed changes in precipitation patterns are now being observed in mulberry-growing areas, with increased extreme rainfall and longer dry spells (Saini *et al*., 2023). Crop evapo-transpiration (ETc) of mulberry is also increasing under future climate scenarios (Kambale *et al.,* 2023).

 Climate change is further affecting insect pest scenario in mulberry growing areas (Seidavi *et al*., 2017). Pests such as Bihar hairy caterpillar, pink mealybug, thrips, leaf webber, and mites now occur more frequently, and diseases like leaf rust and powdery mildew are more common (Seidavi *et al*., 2017). These shifts negatively impact both mulberry nutrition and silkworm performance (Gururaj *et al*., 1999).

**2.1 Mitigation Strategies**

***Use of Climate-Resilient Silkworm and Mulberry Breeds***

 Thermotolerance is critical. Thermo-tolerance is one of the major objectives when breeding climate-resistant silkworms since many important qualitative characters like viability and cocoon traits drop dramatically beyond 28°C (Gani and Ghosh, 2018). Twenty-four bivoltine silkworm germplasm resources were subjected to evaluation for thermal stress tolerance significant variation based on nine genetic parameters.

 Thermotolerance is selected for bivoltine silkworms when the pupation rate exceeds 70% (Chandrakanth *et al.,* 2015). Also, marker-assisted breeding has been used to develop silkworm hybrids with resistance to specific pathogens and thermotolerance (He & OSHIKI, 1984).

***Microclimatic Modification in Rearing Houses***

 In rearing, temperature, humidity, air movement, gases and light are key factors (Satish, *et al.,* 2023). To protect sericulture, right environmental control strategies are needed. These include modifying rearing houses with ventilators, humidifiers, and insulation for microclimate stabilization.

***Early Warning Systems and Weather-Based Advisories***

 Indian Space Research Organisation (ISRO) employed these technologies together with Central Silk Board of India to identify potential areas for mulberry cultivation using remote sensing and GIS (Sun, *et al.,* 2012). Such mapping enables pre-emptive planning of rearing cycles based on climate advisories. Moreover, weather-based early warning systems help in minimizing losses due to extreme events, guiding farmers in schedule adjustment and variety selection (Sharma, *et al.,* 2022).

**3. BIOTECHNOLOGICAL INNOVATIONS IN SERICULTURE**

### ****3.1 Molecular Marker-Assisted Breeding****

 Molecular markers play a crucial role in improving mulberry and silkworm genetics by overcoming limitations of conventional breeding. Marker assisted selection (MAS) enables the breeder to select desirable hybrids at the seedling stages, free from environmental interference, time saving, accurate and precise (Staub, *et al*., 1996). Markers like RAPD, AFLP, ISSR, SSR, and SNP are used in mulberry to enhance traits such as leaf yield, stress tolerance, and disease resistance. Notably, different DNA markers such as restriction fragment length polymorphism (RFLP), random amplified polymorphic DNA (RAPD), amplified fragment length polymorphism (AFLP), inter simple sequence repeat (ISSR), simple sequence repeats (SSR) and single nucleotide polymorphism (SNP) (Lusser, *et al.,* 2012) have contributed significantly to QTL mapping and germplasm characterization. Major advances include the development of QTL maps for water use efficiency and yield traits using RAPD and ISSR markers (Mishra , 2014; Naik, *et al.,* 2014).

 In Bombyx mori, over 400 mutations across 217 loci aid in genetic improvement. More than 400 visible mutations have been placed in the linkage maps which represent 217 loci consisting of mostly morphological and a few isozyme markers (Doira, 1992). These markers have been used to identify genetic diversity, track traits such as thermotolerance, and develop elite races. Research has shown that PCR-based markers and ISSR techniques provide high-resolution insights into population structures and phylogenetic relationships (Chandrakanth, *et al*., 2014; Nagaraju, *et al.,* 2001).

### ****3.2 Transgenic and Genomic Approaches****

 Transgenic technologies in sericulture enable the expression of foreign genes in silkworms and mulberry. In Bombyx mori, systems like PiggyBac and BmNPV have been used to produce recombinant proteins such as human serum albumin and erythropoietin (Maeda, *et al.,* 1985; Alam, *et al.,* 2022; Muneta, *et al*., 2004). Use of transgenic silkworms to produce different recombinant protein has also become a reality now a days (Kojima, *et al*., 2007; Tomita *et al*., 2003. To address issues of protein degradation in the BmNPV system, cysteine protease-depleted baculovirus and Bac-to-Bac systems have been developed, allowing high-yield expression of foreign proteins such as FMDV capsid proteins for veterinary vaccines (Luckow *et al*., 1993; Motohashi ,*et al*., 2005; Li, *et al*., 2008).

 In mulberry, genes like Osmotin and HVA1 enhance stress tolerance. Mulberry transgenics developed with the osmotin gene under a drought inducible promoter showed abiotic stress tolerance and tolerance against biotic fungal pathogens (Das, *et al*., 2011). These approaches broaden sericulture's applications in medicine and stress-resilient farming. Similarly, the HVA1 gene from barley conferred drought, salinity, and cold tolerance in transformed mulberry lines (Checker, *et al*., 2012).

### ****3.3 Tissue Culture and Plant Biotechnology****

 Tissue culture techniques such as micropropagation, organogenesis, and somatic embryogenesis support rapid multiplication and genetic improvement in mulberry. The in vitro culture of cells, tissues, and organs offers unparalleled opportunities for tree improvement (Karnosky , 1981).

 These methods aid in developing stress-tolerant lines and triploids with superior traits (Thorpe, 1983). Over the past two decades, more than 30 successful reports of in vitro regeneration in Indian mulberry varieties such as S-1, V-1, and K-2 have been documented (Chitra & Padmaja, 2002; Kashyap & Sharma, 2006). These approaches, coupled with advancements in molecular breeding and transformation, offer powerful tools for improving productivity and adaptability of mulberry under variable climatic conditions.

### 4. NANOTECHNOLOGY IN SERICULTURE

#### 4.1 Applications in Mulberry Cultivation

 Nanoparticles (NPs) have shown significant potential in enhancing mulberry growth, a crucial factor in sericulture. Nano-fertilizers improve nutrient uptake and boost leaf yield, leading to better silkworm nourishment. Foliar application of nano zinc oxide (ZnO) at 20 ppm in the V-1 mulberry variety resulted in the highest shoot height (96.63 cm), number of branches (8.47), and leaf yield (0.46 kg/plant) with a favourable B:C ratio of 2.93 (Nithya, 2018).

 Iron oxide nanoparticles, applied at 10 mg/kg to soil, significantly enhanced sprouting (82%), number of leaves (52.73% over control), shoot and root biomass (37.20% and 90.24%, respectively), and root length (34%). Chitosan-based NPs, being biodegradable and agriculturally safe, also contribute as effective nano-carriers (Ghormade, *et al*., 2011).

 Foliar applications enable NPs to cross plant barriers via lipophilic and hydrophilic pathways—either through cuticular waxes or aqueous pores and stomata (Schönherr, 2002; Eichert *et al*., 2008; Eichert & Goldbach, 2008), facilitating efficient nutrient delivery.

#### 4.2 Enhancing Silkworm Growth and Cocoon Quality

 Feeding silkworms with NPs-treated mulberry leaves enhances feed conversion, silk yield, and resistance to diseases. TiO₂ NPs (5–10 mg/L) improved ingestion and digestibility, accelerating body weight gain (Li, *et al*., 2016). Silver NPs also improved food consumption and digestibility in larvae (Mathivanan, 2011). Riboflavin NPs increased production and metabolism rates (Kamala & Karthikeyan, 2019).

 Growth parameters like larval length and weight were significantly higher when fed with leaves treated with silver NPs or in combination with spirulina (Meng, *et al.,* 2017). TiO₂ NPs activated the insulin pathway in silkworms, enhancing nutrient metabolism (Tian, *et al*., 2016). Application of ZnO and CuNPs improved larval weight and reduced moulting duration (Shruti, *et al.,* 2019).

 Cocoon traits, such as weight, shell ratio, and filament length, improved with NPs like gold (Patil, *et al*., 2017), riboflavin (Kamala & Karthikeyan, 2019), TiO₂, and AgNPs (Prabu, *et al.,* 2011). These enhancements are linked to the stimulation of enzymatic and hormonal activity in silkworms.

 In terms of disease resistance, TiO₂ NPs inhibited BmNPV proliferation and improved survival rates (Xu*, et al.,* 2015; Zhao*, et al.,* 2020; Fometu, *et al.,* 2022). Silica NPs altered BmNPV morphology, reducing infectivity (Das, *et al.,* 2013). AgNPs showed antibacterial effects against gut bacteria and pathogens like Bacillus spp. (Li, *et al.,* 2013; Ramamoorthy, *et al.,* 2019). Chitosan and silver NPs were effective against bacterial infections, with chitosan exhibiting antimicrobial activity even at 0.2% concentration (Madhusudhan, *et al*., 2023).

 Thymoquinone-encapsulated chitosan NPs (Tq-Chs NPs) also demonstrated antioxidant and anti-inflammatory effects, enhancing silkworm immunity (Hassan, *et al*., 2020). The high surface area of these NPs improves their microbial binding capacity, disrupting pathogen membranes (Ahmad, *et al*., 2013).

Overall, nanotechnology offers a sustainable means to enhance mulberry productivity, silkworm health, cocoon quality, and disease resistance in sericulture (Pradip, *et al*., 2024).

### 5. EMERGING TECHNOLOGIES IN REARING AND MONITORING

#### ****5.1 Smart Rearing Practices****

 Recent innovations have modernized sericulture practices through climate automation and digital monitoring. Climate-controlled rearing houses allow for precise control of temperature, humidity, and ventilation, reducing the risk of disease outbreaks and increasing the survival rate of silkworms (Buhroo, *et al*., 2018; Bhakta *et al*., 2022; Kumari, 2022). These chambers improve silkworm health and produce consistent, high-quality silk.

 Incorporating digital sensors and Internet of Things (IoT) tools into rearing practices has further enhanced precision. Digital monitoring systems, powered by the Internet of Things (IoT), have introduced a new level of precision and efficiency in sericulture, enabling real-time monitoring of silkworm health, feed intake, and ambient conditions (Panwar, *et al*., 2022; Farooq, 2023). This integration helps optimize resource use and improves decision-making processes.

 The use of Arduino-based IoT systems combined with image processing: Technological innovation has resulted in accomplishment of improving silk quality by controlling environmental parameters using Arduino-aided Internet of Things (IoT), image processing technique and smart sensors (Rokhade, *et al*., 2021). These systems are also described as easy to learn, maintain and cost-effective. Additionally, automation in tray movement and mulberry leaf handling enhances labor efficiency. Mechanized tools such as semi-humidifier cum heater, disinfectant dusting machine, and matured silkworm separator (Chanotra & Bali, 2019) have been introduced, while innovations like the Farmer’s friendly mulberry plant cutter offer practical mechanization in leaf harvesting (Kumar, *et al*., 2021).

#### ****5.2 Waste Utilization and Circular Practices****

 Modern sericulture integrates circular economy concepts by converting waste into valuable by-products. Innovations include the use of mulberry leaves as compost, the recycling of sericultural waste, and the utilization of silkworm pupae for animal feed or biofuel production (Rheinberg, 1991; Dukare, *et al*., 2024). These practices reduce environmental load and create new income opportunities. Furthermore, the authors note that waste reduction and recycling lower production costs and promote sustainability, supporting the adoption of eco-friendly methods in silk farming. The use of pupae in animal feed and other sericulture by-products in biodegradable plastics reflects an industry shift toward integrated and sustainable farming systems (Manjunath, *et al*., 2020).

These technologies contribute not only to environmental sustainability but also to economic upliftment, particularly in rural regions where sericulture is a primary livelihood.

### ****6. SOCIOECONOMIC IMPACT AND ADOPTION CHALLENGES****

 Technological and genetic innovations in sericulture have significantly impacted rural livelihoods. Sericulture has emerged as a **stable source of income** for rural households, particularly in developing countries, due to its integration of modern techniques that boost productivity and profitability (Manjunath, *et al*., 2020; Ma *et al*., 2019; Kiyokawa, 1984; Rahmathulla, *et al*., 2012; Tanzi, 2022).

 **Women play a pivotal role in sericulture**, often managing silkworm rearing and cocoon harvesting. Advancements such as climate-controlled rearing houses and automated machines have reduced physical labor and increased output, allowing women to gain better income opportunities. This shift has led to improvements in their **economic status and social standing** (Tzenov, *et al*., 2021; Rajesh and Muchie, 2022). These developments support **greater gender equality and economic inclusion.**

 However, despite these benefits, **barriers to adoption remain**. High **initial investment costs** for modern equipment, a **lack of technical training**, and **limited awareness** among traditional farmers inhibit the widespread implementation of advanced practices (Sharma *et al*., 2022; Ikram and Sharma, 2022). These constraints are especially pronounced in remote rural areas where access to institutional support is minimal. To address these challenges, **inclusive policies** are needed. Literature suggests the importance of government-supported initiatives, including **skill development programs**, **financial subsidies**, and **awareness campaigns**, to bridge the technological divide in sericulture (Panwar *et al*., 2022; Anbarasan and Ramesh, 2022). Additionally, **biotechnology and genetic research** should be extended to marginal farmers through public-private partnerships to ensure equitable access to innovation (Deepika *et al*., 2024; Altman and Farrell, 2022).

 Finally, as **global demand for high-quality silk** continues to rise, ensuring **equitable participation of women and rural youth** is essential for the long-term sustainability and competitiveness of the silk industry (Anushi *et al*., 2024; Leal‐Egaña and Scheibel, 2010). By enabling these populations to access and benefit from technological advances, sericulture can continue to be a vehicle for **rural development and social empowerment**.

 **To better visualize the multidimensional innovations transforming sericulture, Table 1 presents a consolidated overview. It integrates technological, genetic, sustainable, biotechnological, and socioeconomic interventions along with their respective impacts on silk production, quality, and long-term industry resilience. This synthesis highlights how these advancements collectively support the transition toward a more productive, eco-friendly, and inclusive sericulture model.**

# Table 1: Comprehensive Innovations and Impacts in Sericulture

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| Category | Innovation / Practice | Description | Impact on Silk Production | Impact on Silk Quality | Long-Term Benefit |
| Technological Innovations | Automated Silk Reeling Machines | Automates reeling, reduces waste | Increases efficiency and consistency | Enhances thread uniformity and quality | Higher production rate with better consistency |
|  | Climate-Controlled Rearing Houses | Regulates environment | Reduces disease and improves yield | Produces consistent, high-quality silk | Stable production environment |
|  | Digital Monitoring Systems | IoT-based real-time monitoring | Optimizes resources and decision-making | Ensures traceability and quality control | Data-driven sericulture management |
| Genetic Improvements | High-Yield Silkworm Varieties | Selective breeding for more silk | Ensures higher output and consistency | Maintains or improves fiber quality | Reliable silk supply |
|  | Quality Enhancement through Breeding | Modifies tensile strength, elasticity, luster | May slightly reduce yield | Enhances market value and versatility | Premium silk for diverse uses |
|  | Colored Silk Production | Genetically engineered natural colors | Cuts dyeing costs | Eco-friendly and visually appealing | Sustainable and market-attractive product |
| Sustainable Practices | Organic Sericulture | Avoids synthetic chemicals | May lower yield short-term | Produces eco-friendly silk | Long-term sustainability |
|  | Integrated Pest Management (IPM) | Uses natural controls instead of pesticides | Reduces losses and environmental harm | Avoids chemical residues | Environmentally safe pest control |
|  | Waste Reduction & Recycling | Composting, pupae reuse | Cuts costs, promotes sustainability | Minimal direct impact but eco-friendly contribution | Circular economy in sericulture |
| Biotechnology | Silk Protein Engineering | Tailors proteins for medical/industrial use | Expands use beyond textiles | Specialized superior properties | High-value silk innovations |
|  | Transgenic Silkworms | Produces recombinant proteins/substances | Enables pharma and biotech applications | Extends functional uses of silk | Biotechnological commercialization |
|  | Silk-Based Biomaterials | Silk for implants, tissue scaffolds, etc. | May reduce textile focus | Creates high-value, medical-grade silk products | Broadened industrial applications |
| Economic & Social Impact | Empowering Rural Communities | Enhanced income via modern techniques | Increased productivity and profitability | - | Sustainable livelihoods |
|  | Women Empowerment | Women-centric practices benefit from modernization | Better income opportunities | Higher economic status and social equality | Inclusive development |
|  | Global Silk Market Competitiveness | Efficiency and quality boosts international demand | Higher exports and revenue | Stronger global position | Economic growth for producer countries |

## ****7. CONCLUSION AND FUTURE PROSPECTS****

 The transformation of sericulture from a traditional craft to a modern, science-driven enterprise is both necessary and achievable. As this review highlights, the convergence of biotechnology, nanotechnology, and climate-smart innovations holds the potential to revolutionize silk production across all stages—from mulberry cultivation to cocoon harvesting and post-rearing processes. Technologies such as molecular marker-assisted breeding, transgenic silkworm development, and nano-enhanced nutrition have demonstrated significant promise in improving both yield and quality. In parallel, climate-controlled rearing systems and IoT-based monitoring tools offer practical solutions for sustaining sericulture under increasingly erratic weather conditions. Furthermore, the adoption of sustainable practices such as organic farming, waste valorization, and integrated pest management aligns with the global agenda of environmental conservation and circular economy.

 To realize these advancements at scale, multi-stakeholder collaboration involving research institutions, industry players, policy makers, and farming communities is essential. Capacity building, affordable access to technologies, and digital literacy will be critical in empowering sericulture practitioners to embrace and benefit from these innovations. Ultimately, with the right investment and vision, sericulture can emerge as a model of sustainable rural development, blending tradition with technology.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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