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### Bioresource potential of the mulberry–silkworm ecosystem: A circular bioeconomy perspective

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#### Abstract

Sericulture, historically regarded as a silk-centric production system, has evolved into a diversified bioresource industry with strong economic, environmental and social significance. Traditionally focused on cocoon production for raw silk, the sector now generates a wide spectrum of commercially valuable products and by-products derived from mulberry biomass, silkworm rearing residues, grainage components and reeling waste streams. Scientific advancements in biotechnology, biomaterials, nutraceuticals and industrial chemistry have uncovered high-value compounds such as polyphenols, anthocyanins, cellulose nanofibres, chitin, chitosan, fibroin and sericin embedded within previously neglected sericulture residues. Mulberry leaves, stems, bark, fruits and roots are now extensively utilized in livestock feed formulations, functional foods, cosmeceuticals, herbal pharmaceuticals and biodegradable composites, contributing to resource efficiency and rural income diversification. Similarly, silkworm litter, exuviae, dead larvae, pupae and pierced cocoons are being channelled into organic fertilizers, aquafeed, spun silk, biomedical textiles, bioenergy and high-value protein recovery. Reeling waste has emerged as a major industrial raw material through innovations such as non-woven silken fabrics, sericin-based skincare formulations and fibroin-driven medical scaffolds. The full utilization of these value streams enhances livelihood resilience among rural households, strengthens women-led entrepreneurship and supports climate-smart circular economies by minimizing waste and improving resource-use efficiency. To sustain this transition, strategic interventions in technology dissemination, enterprise incubation, market integration and policy support are critical. Altogether, sericulture demonstrates a successful transformation from a single-output textile enterprise into a multi-sectoral bioindustrial platform capable of serving global markets across textiles, health, cosmetics, agriculture and biomaterials.

**Keywords:** Sericulture, mulberry biomass, silkworm residues, reeling waste, bioresource utilization

#### 1. Introduction

Sericulture represents one of the most significant agro-based rural enterprises in Asia, particularly in countries such as India and China, where it plays a pivotal role in employment generation, women's empowerment, and decentralized livelihood security. In the Indian context, sericulture sustains millions of small and marginal farmers through a low-investment, labor-intensive production model that is well suited to rural socio-economic conditions. According to the Food and Agriculture Organization of the United Nations (FAO, 2019) [7], silk production contributes substantially to income diversification, poverty alleviation, and resilience building among rural households in developing economies. Traditionally, sericulture has been viewed as a mono-output enterprise primarily focused on cocoon production and filament silk extraction. However, contemporary scientific and industrial perspectives increasingly recognize the mulberry–silkworm agro-ecosystem as a diversified bioresource system. Beyond raw

silk, it generates multiple value-added by-products, including pupal biomass, sericin, reeling waste, composted litter, and bioactive compounds with applications in nutraceutical, pharmaceutical, and cosmetic industries. This paradigm shift highlights sericulture as an integrated bioeconomic model rather than a single-commodity production system.

Furthermore, advancements in varietal selection and crop management have underscored the importance of selecting nutritionally superior mulberry genotypes and implementing stage-specific leaf harvesting strategies. Such scientific interventions enhance silkworm growth, cocoon quality, and overall silk productivity while maintaining system sustainability. As emphasized by Nitish *et al.* (2026), optimizing leaf quality according to larval instar requirements significantly improves feed conversion efficiency and economic returns, thereby strengthening the productivity and resilience of the sericulture production system.

Emerging research has repositioned sericulture within the framework of circular bioeconomy, where agricultural biomass, insect-derived residues, and processing waste streams are recycled and reintegrated into productive chains (Kumar *et al.*, 2022; Jaiswal & Mandal, 2022) <sup>[12, 10]</sup>. This paradigm shift recognizes sericulture not merely as a textile-linked activity but as a multi-stream bioresource system capable of contributing to sustainable agriculture, renewable energy, nutraceutical industries, biomedical materials, and organic farming inputs. The present review synthesizes peer-reviewed evidence on mulberry-based bioresources, silkworm rearing by-products, grainage residues, and reeling waste, emphasizing their biochemical composition, industrial applications, and sustainability implications.

## 2. Mulberry-Based Bioresources

Mulberry cultivation (primarily *Morus alba* L.) is fundamentally aimed at leaf production for silkworm feeding. Nevertheless, only a fraction of total plant biomass is directly utilized in rearing operations. Significant quantities of leaves (surplus or aged), fruits, bark, stems, and roots remain underexploited despite their rich phytochemical and structural composition. Scientific exploration over the past two decades has revealed substantial pharmaceutical, nutraceutical, and biomaterial applications of these plant components.

### 2.1 Mulberry Leaves: Nutraceutical and Functional Applications

Mulberry leaves represent a reservoir of bioactive compounds with therapeutic potential. Biochemical analyses indicate that leaves contain 15–31% crude protein (dry weight basis), balanced essential amino acids, minerals such as calcium, iron, magnesium, and potassium, along with abundant secondary metabolites including flavonoids, rutin, quercetin, chlorogenic acid, and alkaloids (Suo *et al.*, 2021) <sup>[30]</sup>. Among these compounds, 1-deoxynojirimycin (DNJ) has attracted significant scientific attention due to its potent  $\alpha$ -glucosidase inhibitory activity, which delays carbohydrate digestion and glucose absorption (Chen *et al.*, 2019) <sup>[5]</sup>. This mechanism underlies the anti-diabetic properties of mulberry leaf extracts.

Clinical investigations have demonstrated that regular consumption of mulberry leaf tea reduces postprandial hyperglycemia, improves lipid metabolism, and lowers serum triglyceride levels (Kim *et al.*, 2011) <sup>[11]</sup>. Polyphenolic extracts exhibit strong antioxidant capacity by scavenging reactive oxygen species and reducing oxidative stress markers. Anti-inflammatory activity mediated through modulation of NF- $\kappa$ B pathways has also been documented (Hardoko & Yulinery, 2022) <sup>[8]</sup>.

Beyond human nutraceutical applications, mulberry leaves serve as a high-digestibility fodder for livestock. Comparative feeding trials have shown improved milk yield in dairy cattle and enhanced weight gain in goats when mulberry foliage supplements conventional fodder systems (Benavides *et al.*, 2002; Mandal *et al.*, 2020) <sup>[3, 18]</sup>. The integration of mulberry into mixed farming systems thus increases land-use efficiency and farm-level income diversification.

### 2.2 Mulberry Fruits and Phytochemical Extracts

Mulberry fruits contain substantial concentrations of anthocyanins, particularly cyanidin-3-glucoside and cyanidin-3-rutinoside, which confer strong antioxidant capacity (Özgen *et al.*, 2009) <sup>[21]</sup>. In addition to anthocyanins, fruits possess resveratrol, phenolic acids, and vitamin C, contributing to cardioprotective and anti-aging effects.

Industrial applications of mulberry fruit extracts have expanded into functional beverages, herbal syrups, nutraceutical capsules, and cosmetic formulations. The antioxidant profile supports their use in anti-aging skincare and dermatological preparations (Bae & Suh, 2021) <sup>[2]</sup>. Fermentation-based processing has further enabled development of probiotic beverages and value-added food products, enhancing market potential and profitability.

### 2.3 Mulberry Bark and Wood-Based Materials

Mulberry bark and woody biomass are traditionally underutilized components of sericulture plantations. However, chemical characterization reveals high cellulose and hemicellulose content along with lignin and triterpenoids such as betulinic acid (Wang *et al.*, 2018) <sup>[31]</sup>. Recent advancements in nanotechnology have enabled extraction of cellulose nanowhiskers and nanofibrils from mulberry bark for biomedical films, wound dressings, and biodegradable packaging materials (Liu *et al.*, 2022) <sup>[16]</sup>.

Natural fiber composites derived from mulberry bark exhibit favorable tensile strength, biodegradability, and low density, making them suitable alternatives to synthetic polymer reinforcements (Ramesh *et al.*, 2020) <sup>[23]</sup>. These developments position mulberry biomass as a sustainable raw material within green material science and bio-based packaging industries.

## 3. Silkworm Rearing By-Products

Silkworm rearing generates multiple secondary residues, including litter (frass), exuviae, and pupae. Historically considered waste, these by-products are now recognized as valuable bioresources contributing to organic farming, biomaterials, food security, and renewable energy.

### 3.1 Silkworm Litter (Frass)

Silkworm litter consists of larval excreta mixed with leftover mulberry leaves. Nutrient profiling indicates significant levels of nitrogen (2–3%), phosphorus, potassium, and micronutrients, rendering it suitable for organic manure application (Hassan *et al.*, 2020) <sup>[9]</sup>. Field trials comparing silkworm litter compost with farmyard manure demonstrate improved mulberry leaf yield, enhanced soil microbial biomass, and increased enzymatic activity (Saha *et al.*, 2018) <sup>[25]</sup>.

Vermicomposting of silkworm litter further enhances nutrient mineralization and humus formation, improving soil structure and water retention capacity (Sivaprasad *et al.*, 2021) <sup>[28]</sup>. Additionally, anaerobic digestion studies report promising methane yields, indicating its viability as a substrate for biogas production (Lakshmi & Rao, 2021) <sup>[14]</sup>. Such integration supports energy self-sufficiency in sericulture clusters while reducing environmental waste load.

### 3.2 Exuviae and Chitosan Extraction

Molted exuviae represent an alternative source of chitin, a structural polysaccharide found in insect cuticles. Extraction and deacetylation yield chitosan, a biopolymer with antimicrobial, biodegradable, and biocompatible properties (Chandrappa *et al.*, 2021) <sup>[4]</sup>. Compared to crustacean-derived chitosan, insect-based sources may reduce allergenic risks and seasonal supply limitations (Awasthi & Singh, 2023) <sup>[1]</sup>.

Silkworm-derived chitosan has demonstrated applications in wound healing films, drug delivery systems, agricultural seed coatings, and heavy metal adsorption from wastewater. These applications expand the biomedical and environmental relevance of sericulture by-products.

### 3.3 Silkworm Pupae: Nutritional and Industrial Potential

Silkworm pupae account for approximately 45–50% of cocoon biomass and are nutritionally rich. Proximate composition studies reveal 50–60% crude protein and 20–30% lipid content on dry weight basis (Longvah *et al.*, 2012) <sup>[17]</sup>. The amino acid profile includes lysine, methionine, and threonine, supporting their suitability as high-quality protein supplements. Lipid fractions contain significant levels of polyunsaturated fatty acids, including omega-3 ( $\alpha$ -linolenic acid) and omega-6 fatty acids (Zhang *et al.*, 2018) <sup>[32]</sup>.

Enzymatic hydrolysis of pupal proteins yields bioactive peptides exhibiting antioxidant, antihypertensive, and immunomodulatory properties (Subramanian *et al.*, 2020) <sup>[29]</sup>. In livestock and poultry nutrition, silkworm pupae meal effectively substitutes soybean meal and fishmeal without compromising growth performance (Singh & Ahmed, 2022) <sup>[26]</sup>. Furthermore, extraction of pupal oil demonstrates feasibility for biodiesel production and soap manufacturing, contributing to industrial diversification.

### 4. Grainage and Cocoon By-Products

Grainage and cocoon processing units generate several secondary materials that are often undervalued within traditional sericulture systems. During grainage operations, defective, pierced, double, thin-shelled, and cut cocoons are separated because they are unsuitable for conventional filament reeling. Historically, these materials were treated as low-grade waste or sold at minimal value. However, technological advancements in silk spinning and fiber processing have transformed these residues into economically viable raw materials.

Pierced cocoons—resulting from moth emergence—contain discontinuous silk fibers due to the breakage of the filament. Similarly, cut cocoons generated during seed extraction lose filament integrity. Although unsuitable for reeling, these cocoons retain significant fibroin content and can be processed into spun silk yarn. Modern degumming and carding technologies enable recovery of short fibers, which are then converted into high-quality spun silk yarn through ring spinning or open-end spinning systems (Zhou *et al.*, 2019) <sup>[33]</sup>.

Spun silk differs structurally from reeled silk but offers unique textile characteristics, including softness, breathability, and enhanced moisture absorption. Recent textile innovations emphasize blending spun silk with

cotton, wool, viscose, and synthetic fibers to improve durability, reduce production costs, and enhance sustainability (Ravikumar & Awasthi, 2022) <sup>[24]</sup>. Blended fabrics also reduce dependence on virgin synthetic fibers, aligning textile manufacturing with circular economy principles.

Additionally, cocoon shell powder derived from damaged cocoons is increasingly explored for cosmetic exfoliants, protein supplements, and biodegradable composite fillers. Such diversification enhances the economic efficiency of grainage units and reduces material loss across the production chain.

### 5. Reeling Waste, Sericin and Fibroin Recovery

The silk reeling and processing industry produces substantial quantities of protein-rich effluents and fibrous waste. Traditionally, degumming wastewater containing sericin was discharged into aquatic systems, contributing to environmental pollution. Contemporary research, however, has reframed sericin and fibroin as high-value biomolecules with significant biomedical and industrial potential.

#### 5.1 Sericin

Sericin is a hydrophilic globular protein that envelops fibroin filaments within the cocoon. During degumming, sericin is removed using hot alkaline solutions, accounting for approximately 20–30% of cocoon weight. Historically considered a waste effluent, sericin is now recognized for its biofunctional properties and industrial versatility.

Biochemically, sericin contains high proportions of serine, aspartic acid, glycine, and threonine, conferring strong hydrophilicity and moisture-retention capacity. Its antioxidant activity is attributed to hydroxyl-containing amino acids capable of scavenging reactive oxygen species (Singh *et al.*, 2017) <sup>[27]</sup>. Experimental studies demonstrate antimicrobial activity against common pathogens, making sericin suitable for dermatological and wound-care applications (Kundu *et al.*, 2018) <sup>[13]</sup>.

In the cosmetic industry, sericin is incorporated into moisturizing creams, shampoos, anti-aging formulations, and hair-conditioning agents due to its film-forming and UV-protective properties. In food science, it is being developed into biodegradable edible coatings and films for extending shelf life of perishable products (Park & Yamada, 2021) <sup>[22]</sup>. Its ability to form biocompatible hydrogels also supports applications in drug encapsulation and controlled release systems.

Green extraction methods—such as enzyme-assisted degumming, membrane filtration, and spray drying—have significantly improved sericin recovery efficiency while reducing chemical load in effluents. These innovations convert a major industrial waste stream into a commercially valuable biomolecule.

#### 5.2 Fibroin

Silk fibroin is the primary structural protein responsible for the remarkable mechanical strength and elasticity of silk fibers. It is composed predominantly of repetitive glycine–alanine sequences forming  $\beta$ -sheet crystalline domains, which confer tensile strength and structural stability. Its biocompatibility, biodegradability, and minimal immunogenicity have positioned fibroin as a leading natural

biomaterial.

Biomedical research has demonstrated the versatility of silk fibroin in wound dressings, where it promotes cell adhesion, accelerates epithelialization, and enhances tissue regeneration (Lawrence *et al.*, 2020) <sup>[15]</sup>. Fibroin scaffolds are extensively investigated for tissue engineering applications, including bone, cartilage, ligament, and nerve regeneration. Porous fibroin matrices support cell proliferation and extracellular matrix deposition (Chen *et al.*, 2022) <sup>[16]</sup>.

Controlled drug delivery systems utilizing fibroin nanoparticles enable sustained release of antibiotics, anticancer agents, and growth factors. Additionally, silk fibroin films and sponges are being explored in regenerative medicine for artificial skin and corneal repair.

Emerging applications in 3D bioprinting demonstrate the ability of fibroin-based bioinks to maintain structural fidelity while supporting cell viability (Miyamoto *et al.*, 2023) <sup>[19]</sup>. These advancements extend silk utilization far beyond textiles into high-value biomedical technologies.

## 6. Economic and Sustainability Significance

The valorization of sericulture residues aligns strongly with circular bioeconomy frameworks, which emphasize resource efficiency, waste minimization, and closed-loop production systems. By transforming biological waste streams—such as frass, pupae, pierced cocoons, sericin effluents, and reeling waste—into commercially valuable inputs, sericulture reduces environmental burden while diversifying revenue streams.

Integration of composting units, pupae processing plants, and silk waste spinning facilities within rural sericulture clusters can substantially enhance employment opportunities. Women and small-scale entrepreneurs particularly benefit from decentralized processing enterprises such as vermicomposting, nutraceutical preparation, and spun silk production.

From an environmental perspective, replacement of petroleum-derived polymers with silk proteins and biodegradable composites reduces microplastic generation and greenhouse gas emissions. Life-cycle analyses indicate that silk-based biomaterials exhibit lower carbon footprints compared to synthetic polymers (Jaiswal & Mandal, 2022) <sup>[10]</sup>. The multi-output nature of sericulture improves resource-use efficiency per unit land area, reinforcing its sustainability credentials.

Thus, sericulture represents an integrated agro-industrial model combining agriculture, entomology, biotechnology, materials science, and renewable energy production (Kumar *et al.*, 2022) <sup>[12]</sup>.

## 7. Challenges and Research Gaps

Despite substantial progress, several technological, regulatory, and market-related challenges limit full-scale adoption of sericulture residue valorization.

### 7.1 Infrastructure Limitations

Decentralized extraction and processing infrastructure remains inadequate in many rural sericulture regions. Advanced recovery technologies for sericin, chitosan, and fibroin require capital investment and technical training, which may not be readily accessible to smallholders.

### 7.2 Regulatory and Food Safety Constraints

Although silkworm pupae are consumed in several Asian countries, regulatory frameworks governing edible insect products remain inconsistent. Standardization of safety protocols, allergen assessments, and quality certification is essential for broader market acceptance.

### 7.3 Standardization of Green Extraction Protocols

Chemical-intensive degumming and chitin extraction processes raise environmental concerns. Development of enzyme-assisted, solvent-free, and energy-efficient extraction technologies is crucial to maintain sustainability claims.

### 7.4 Limited Clinical Validation

While laboratory-scale biomedical applications of sericin and fibroin show promise, large-scale clinical trials remain limited. Regulatory approvals and translational research pathways must be strengthened.

### 7.5 Market Linkage Constraints

Rural clusters often lack structured supply chains for nutraceuticals, biomaterials, and insect-based feed products. Policy interventions and cooperative marketing models are needed to ensure equitable value distribution.

Future research should prioritize life-cycle assessments, techno-economic feasibility studies, enzyme-assisted processing, and scalable enterprise models (Kumar *et al.*, 2022) <sup>[12]</sup>. Integration of digital platforms and traceability systems may further enhance market transparency and consumer trust.

## 8. Conclusion

The sericulture ecosystem centered around *Bombyx mori* represents a paradigmatic transition from a single-product silk industry to a diversified bioresource platform. Mulberry biomass, silkworm rearing residues, grainage waste, and reeling by-products collectively contribute to applications spanning nutraceuticals, livestock feed, biodegradable materials, renewable energy, biomedical engineering, and sustainable textiles.

Scientific advancements in protein chemistry, biomaterial engineering, insect nutrition, and circular economy modeling have significantly expanded the industrial relevance of these by-products. However, realizing their full potential requires interdisciplinary collaboration among agronomists, entomologists, biotechnologists, material scientists, policymakers, and rural entrepreneurs.

With appropriate technological scaling, supportive regulatory frameworks, and integrated value-chain development, sericulture can serve as a model for sustainable rural bioeconomy development—combining ecological resilience, economic diversification, and social inclusion within a circular production paradigm.

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