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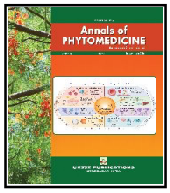

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Sericin-based formulations for skin and hair care: From waste valorization to multifunctional cosmeceuticals

M. Sabiya Sulthana*, P. Mangammal◆, K. A. Murugesh*, K. Raja*** and M. Senthilkumar******

** Department of Sericulture, Forest College and Research Institute, Mettupalayam-641 301, Tamil Nadu, India*
*** Horticultural College and Research Institute, Paiyur-635 112, Tamil Nadu, India*
**** Centre for Agricultural Nanotechnology, TNAU, Coimbatore-641 003, Tamil Nadu, India*
***** Department of Agricultural Microbiology, TNAU, Coimbatore-641 003, Tamil Nadu, India*

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Abstract

Silk sericin, a glycoprotein making up 25-30% of *Bombyx mori* silk cocoons represent the successful valorisation of an industrial waste stream into a multipurpose and sustainable cosmeceutical ingredient. Traditionally, this protein discarded as waste during silk degumming, now reclaimed for its remarkable biochemical properties including potent humectancy, antioxidant capacity and film-forming capabilities that are in lines with the principles of clean beauty. This review details the complete cycle of sericin from its biosynthesis and molecular characterisation in the silk gland to sophisticated, environmental friendly extraction techniques that recover the protein from wastewater. It thoroughly evaluates the sericin's proven effectiveness in skincare and haircare where it enhances skin barrier function, reduces hyperpigmentation, speeds up wound healing and fortifies hair. The study also examines its multifaceted formulation science from emulsions and serums to nanoparticles and analyses the developing commercial sector driven by eco-conscious consumers. Finally, it addresses key issues in standardization and safety while outlining future perspectives that position sericin as a cornerstone of circular economy innovation in the cosmetic and biomedical industries.

1. Introduction

Sericin, the glue-like protein comprising 25-30% of raw silk cocoons, has long been discarded as wastewater during degumming but now stands at the forefront of sustainable cosmeceuticals due to its exceptional humectant, antioxidant and film-forming abilities that mimic human skin's natural moisture barrier (Kabir *et al.*, 2024). Extracted primarily from *B. mori* silkworms, this serine and glycine rich glycoprotein (molecular weight 10-400 kDa) binds water up to three times its weight, inhibits tyrosinase for antiageing effects and promotes collagen synthesis, making it ideal for multifunctional skincare and haircare products amid rising demand for clean beauty alternatives to synthetic polymers (Aad *et al.*, 2024).

Global silk production reached approximately 109,000 tons in recent years, generating an estimated 27,000-54,000 tons of sericin annually as byproduct equivalent to 25-50% of cocoon weight, much of which pollutes waterways in major producers like China (80% share), India and Brazil (Mathew *et al.*, 2024). In India, the world's second-largest silk producer with 35,000-38,000 tons yearly (primarily mulberry silk from Karnataka and Tamil Nadu), sericin output hovers around 8,000-12,000 tons per year, underscoring vast untapped potential for waste valorization in a nation where sericulture supports 9 million rural livelihoods (Kabir *et al.*, 2024).

Corresponding author: Dr. P. Mangammal
Assistant Professor (Sericulture), Horticultural College and Research Institute, Paiyur-635 112, Tamil Nadu, India
E-mail: mangammal.p@tnau.ac.in
Tel.: +91-9597956268

This review explores sericin's journey from sericulture effluent to high-value cosmeceuticals, covering innovative extractions, skin/hair formulations (*e.g.*, nanoemulsions with rice water), clinical efficacy data showing 25-40% hydration gains, safety profiles and market projections to $4-6 billion by 2035 driven by eco-conscious consumers (Dragojlov *et al.*, 2025).

2. Fundamentals of Silk Sericin

Silk sericin comprising 25-30% of *B. mori* cocoons by dry weight, functions as nature's protective glycoprotein coating that encapsulates fibroin filaments. The following sections systematically elucidate its biosynthesis, molecular architecture and structure-function relationships that underpin its transformation from silk industry byproduct to high-value cosmeceutical active. These foundational principles inform subsequent discussions on extraction optimization, formulation strategies and commercial scalability across skincare applications.

2.1 Biosynthesis and natural role

Sericin biosynthesis occurs exclusively in the middle silk gland (MSG) of *B. mori* silkworms during the fifth and final larval instar, where specialized columnar epithelial cells in three sub-regions: Posterior A-zone, middle B-zone and anterior C-zone coordinate gene expression under hormonal control from ecdysone and juvenile hormone (Takasu *et al.*, 2007; Chen *et al.*, 2022). Takasu *et al.* (2007) identified Ser3 as the novel anterior-specific isoform in the C-zone, complementing Ser1 (dominant in A/B-zones, 70-80% total) and Ser2 with transcription peaking on day 7 *via* silk gland factor-1 (SGF-1) binding to promoter SA sites for massive output up to 20-35% of larval body weight in proteins over 3-4 days. These isoform synthesized on rough endoplasmic reticulum and Golgi-processed with glycosylation, secrete as a viscous dope (15-25% w/v, pH 6.8-

7.2) that flows anteriorly to coat fibroin brins from the posterior silk gland (PSG) (Wu *et al.*, 2024).

In its natural role, sericin acts as a hydrophilic glue enveloping fibroin fibers in three concentric layers (Ser1 bulk, Ser2 middle, Ser3 surface) to form the cocoon's outer shell (20-35% mass, 0.3-0.5 g/cocoon), which Kunz *et al.* (2016) describe as undergoing shear-thinning extrusion through the spinneret, followed by rapid dehydration and hydrogen bonding for solidification into a semi-crystalline barrier. This structure reduces water loss by over 90%, resists microbial penetration *via* embedded antimicrobial peptides and withstands mechanical stress during the 10-14 day pupal diapause, with Välisalmi and Linder (2024) quantifying optimal fibroin:sericin ratios (75:25) for extensional dope rheology that prevents premature gelation (Välisalmi and Linder, 2024). Chen *et al.* (2022) further demonstrate through ectopic PSG expression that MSG's superior secretory efficiency boosts sericin content 3-4 fold without gland deformity, while Wu *et al.* (2024) characterized the stable 150 kDa Ser150 variant enhancing layer adhesion (Chen *et al.*, 2022; Wu *et al.*, 2024). Overall, this orchestrated process underscores sericin's evolutionary adaptation for pupal protection, now harnessed for biomaterial innovation (Kunz *et al.*, 2016).

2.2 Chemical and physical composition

2.2.1 Amino acid profile

Sericin from *B. mori* cocoons features a distinctive amino acid profile comprising 18 residues in unit of mole percent (mol%), dominated by serine (28-40 mol%), glycine (15-20 mol%) and aspartic/asparagine (12-18 mol%) with threonine (~10%), glutamic acid (~8%) and alanine (5-7%) as significant contributors (Wang and Zhang, 2011; Cao and Zhang, 2016). These polar residues provide essential functional groups hydroxyl (-OH from Ser/Thr) for hydrogen bonding, carboxyl (– COOH from Asp/Glu) for pH responsiveness and amide (–NH, from Asn/Gln) for solubility forming characteristic repetitive motifs like Ser-Gly-Ser that confer the natural adhesive properties observed in cocoons (Chen *et al.*, 2012). The chemical structure of sericin is shown in Figure 1. Hydrophobic residues such as valine and leucine remain minor (<5%), ensuring surface hydrophilicity, biocompatibility and low immunogenicity that distinguish sericin from the more crystalline fibroin (Saha *et al.*, 2019; Manesa *et al.*, 2020). Table 1 summarises the comparison of amino acid profiles and functions in sericin and fibroin.

Table 1: Sericin vs. Fibroin: Amino acid profiles and functions

Amino acid	Mol% range in sericin	Comparison to fibroin (mol%)	Primary role (Wang and Zhang, 2011; Saha *et al.*, 2019)
Serine	28-40	12	Humectancy, H-bond networks
Glycine	15-20	43	Backbone flexibility in repeats
Aspartic acid / Asparagine	12-18	1-2	pH-triggered swelling, charge
Threonine	~10	<1	Emulsion viscosity control
Glutamic acid	~8	1	Solubility enhancement
Alanine	5-7	29	Minor structural support

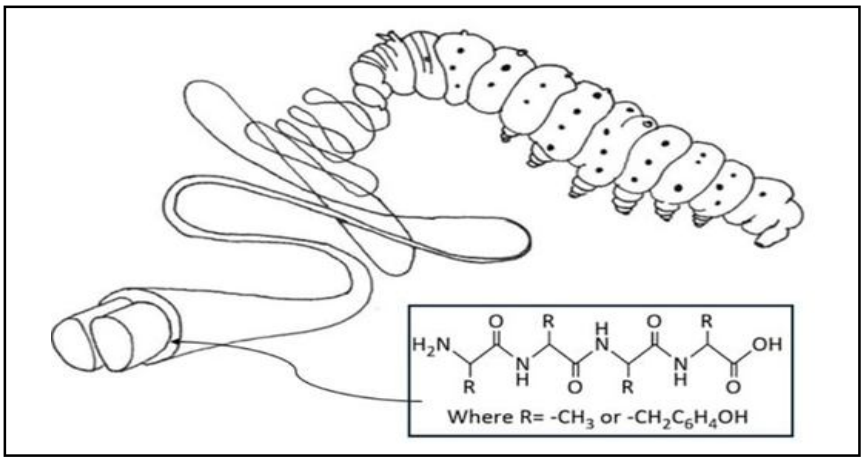

Figure 1: Chemical structure of sericin (Adapted from Aad *et al.*, 2024).

2.2.2 Hydrophilic nature

Sericin's polar amino acid dominance results in a strongly negative hydropathy index (-0.67 to -1.12), enabling it to retain 3-5 times its weight in water, often outperforming hyaluronic acid under physiological conditions (Silva *et al.*, 2022). The three-layered cocoon structure provides functional diversity: Outer Ser1's serine-rich repeats deliver sustained hydration, middle Ser2 offers adhesive properties and inner Ser3's threonine content enhances viscosity in emulsions (Chen *et al.*, 2012; Reis *et al.*, 2025). Glycoprotein components (5-10% β-linked galactose, mannose, xylose) further improve keratin binding on skin and hair, while enabling surfactant-free emulsification; at skin pH 5.5, carboxyl deprotonation induces up to 200% volumetric swelling, reducing trans epidermal water loss by 25-40% in applied films (Saha *et al.*, 2019).

2.2.3 Molecular weight heterogeneity

Sericin exhibits polydisperse molecular weights ranging from 20-400 kDa, corresponding to its three genetic isoforms produced sequentially in middle silk glands: Outer Ser1 (250-400 kDa, highly viscous protective layer), middle Ser2 (150-250 kDa, adhesive interface) and inner Ser3 (150-250 kDa, elastic fiber coating) (Wang and Zhang, 2011; Chen *et al.*, 2012). Table 2 presents the sericin's isoforms along with their molecular weight, cocoon position, suitable extraction methods and applications. Extraction methodology determines the final molecular weight distribution: Gentle enzymatic (proteases at 50-60°C) or hydrothermal (80-100°C, neutral pH) processes preserve high-MW fractions (>200 kDa) suitable for robust gels (G>10 kPa) and breathable films, whereas traditional alkali degumming (Na_2CO_3 boiling at pH 11) yields low-MW oligomers (10-50 kDa) that achieve >95% solubility at room temperature and enhanced transdermal penetration (Yakul *et al.*, 2021; Manesa *et al.*, 2020).

Table 2: Sericin isoforms

Sericin layer/isoform	MW range (kDa)	Cocoon position	Best extraction and application (Wang and Zhang, 2011; Yakul *et al.*, 2021)
Ser1 (Outer)	250-400	Protective coat	Enzymatic/hydrothermal: Thick creams, masks
Ser2 (Middle)	150-250	Adhesive layer	Balanced methods: Lotions, serums
Ser3 (Inner)	150-250	Fiber interface	Alkali: Quick-dissolve sprays, penetrants

2.2.4 Physical properties

Sericin demonstrates an isoelectric point (pI) of 6.5-7.5, ensuring >95% solubility in neutral-to-alkaline aqueous media, thermal stability with decomposition onset at 240-270°C (TGA, 10% weight loss) and pseudoplastic rheology characterized by shear-thinning behavior (viscosity peak of 10-100 cP at 5-15% w/v) driven by intermolecular hydrogen bonding networks (Silva *et al.*, 2022; Reis *et al.*, 2025). Its UV absorbance at 280 nm (from trace tyrosine/tryptophan) provides natural photoprotection, while intrinsic fluorescence (excitation 280 nm/emission 340 nm) facilitates conformational monitoring during gelation (Saha *et al.*, 2019). These properties enable versatile cosmeceutical applications: High-MW fractions for occlusive creams and masks, low-MW variants for rapid-penetration serums and strategic blends for hair conditioners that swell into the cortex (Chen *et al.*, 2012; Saha *et al.*, 2019).

2.3 Key structure-property relationships

Sericin's behavior in formulations is heavily influenced by its ability to adopt two primary secondary structures: The flexible random coil and the ordered β-sheet. Das (2022) explained that in an aqueous environment, sericin predominantly exists in the random coil conformation. In this state, the protein chains are loosely folded, exposing numerous polar groups such as hydroxyl (-OH) and amide ($-NH_2$) side chains. These exposed groups have a strong affinity for water molecules, facilitating extensive hydration which renders sericin highly soluble. The flexible and disordered chains allow sericin to dissolve easily in water and provide excellent chain mobility. This is beneficial for formulations like serums and sprays that require quick dissolution, smooth application and uniform film formation on the skin or hair surface (Swain *et al.*, 2025).

Conversely, Fatahian *et al.* (2021) highlighted that under specific conditions such as changes in temperature, pH, or ionic concentration, sericin molecules start to rearrange into β-sheet structures. This conformation forms when peptide backbones align and hydrogen bond with each other, creating more crystalline and aggregated regions. The formation of β-sheets decreases solubility because these tightly packed structures are less accessible to water. However, this ordered arrangement facilitates gelation by enabling the formation of an intermolecular network, which imparts mechanical strength and stability to sericin-based gels and films. This property is crucial for sustained hydration, therapeutic occlusion and controlled release of actives in biomedical and cosmetic applications. Marwa *et al.* (2023) further elaborated that this β-sheet-rich form improves the durability of sericin films against water wash-off, making it advantageous for protective skincare products such as moisturizing masks.

Das (2022) discussed how formulation scientists can manipulate the balance between these two conformations to customize product performance. By varying sericin concentration, pH, temperature and ionic strength, formulators can control the kinetics and extent of the transition from random coil to β-sheet. A predominance of the random coil structure produces light, fast-absorbing products with excellent solubility, while increasing β-sheet content enhances gel strength and film barrier properties for longer-lasting effects. This tunability allows sericin to be incorporated into a spectrum of products, from lightweight lotions and sprays to thick creams and hair conditioners with targeted delivery and protective functions.

Finally, Mondal *et al.* (2007) synthesized this understanding by emphasizing sericin's structural versatility as a foundational reason for its wide-ranging application potential. The dynamic interplay and controlled modulation between random coil and β-sheet conformations govern sericin's solubility, gelation behavior, rheological properties and biocompatibility. This multifaceted adaptability positions sericin as a valuable biopolymer for various cosmeceutical and biomedical formulations, where balancing hydration, stability and functionality is key.

In essence, the conformation-dependent switch between the hydrated, soluble random coil and the mechanically robust, gel-forming β-sheet enables sericin to serve multiple roles in product design, tailored to deliver optimal performance across diverse skincare and therapeutic applications.

3. Valorization pathways: Sustainable extraction and recovery from waste streams

3.1 Sources for recovery

Sericin procurement fundamentally relies on *B. mori* cocoons as the cornerstone reservoir, where this glycoprotein accounts for 15-35% of total cocoon mass typically averaging 25-30% across commercial bivoltine strains. As the protective outer gum sheath encasing fibroin filaments, extractable at 75-85% efficiency through targeted

degumming processes that deliver unmatched purity for high-performance cosmeceutical scaffolds and biomedical hydrogels (Padamwar and Pawar, 2004; Zhang, 2002). Complementary aqueous streams from sericulture processing namely degumming wastewater and reeling water provide essential secondary recovery avenues. Degumming wastewater carries 0.5-5 g/l solubilized sericin amid substantial COD burdens (4,000-9,000 mg/l) generated during alkaline or soap-mediated solubilization, while reeling water captures residual gum at 0.1-2 g/l during raw silk filament unwinding under warm water immersion (GencTurk, 2020). Both effluents prove reclaimable at 50-90% yields through pH adjustment (to 4.0-5.0), divalent cation ($CaCl_2$) precipitation, or ultrafiltration cascades (10-100 kDa MWCO), followed by dialysis and lyophilization to excise salts, melanoidins and soaps effectively transmuting environmental liabilities into scalable bio resources that approximate native molecular weight polydispersity (10-400 kDa) for industrial biomaterials (Vaithanomsat and Kitpreechavanich, 2008).

3.2 Extraction and purification methodologies

Sericin extraction and purification methodologies have evolved from high-throughput conventional processes prioritizing industrial yield to precision sustainable techniques that preserve molecular integrity, bioactivity and fundamentally shaping the protein's suitability for biomedical and cosmeceutical applications (Bascou *et al.*, 2022). The various extraction methods including conventional and advanced techniques are shown in Figure 2.

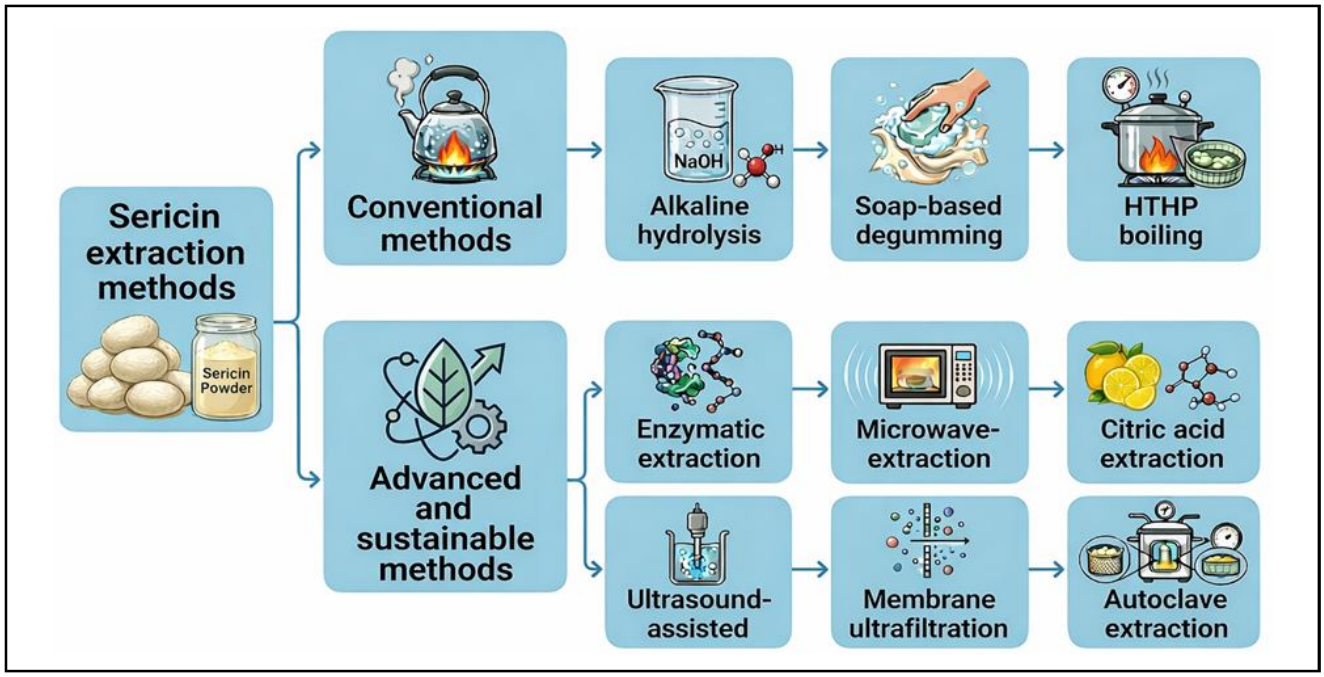

Figure 2: Extraction methods of sericin.

3.2.1 Conventional methods

Alkaline hydrolysis using sodium carbonate (Na_2CO_3, 0.5-2% w/v at 90-100°C for 30-60 min) rapidly solubilizes 25-50% of cocoon sericin through extensive peptide bond cleavage, producing predominantly low molecular weight fragments (<20-100 kDa) accompanied by Maillard reaction toxins and alkaline effluents that complicate downstream wastewater management (Kurmi *et al.*, 2023; Gupta *et al.*, 2014). Soap-based degumming protocols conducted at 80-95°C with neutral Marseille soap achieve 30-45% yields while minimizing fibroin contamination (5-10% versus 15-20% in alkali methods), though thermal stress induces â-sheet to random coil transitions requiring acidification (pH 4.5-5.5) and centrifugation for surfactant-laden sericin recovery (Rocha *et al.*, 2017). High-temperature high-pressure (HTHP) boiling (120-130°C, 2-3 atm for 20-40 min) maximizes extraction efficiency to 50-77% *via* accelerated gum dissolution, yet promotes hydrolytic degradation and glycation necessitating exhaustive dialysis (10-14 kDa MWCO) to attain 80-90% purity suitable primarily for textile applications (Gimenes *et al.*, 2014).

3.2.2 Advanced and sustainable methods

Enzymatic extraction employs alcalase protease (2-5% loading at pH 7.5-8.0, 45-55°C for 2-4 h) to selectively liberate 20-40% of structurally preserved sericin (50-400 kDa) achieving >95% purity post-centrifugation and ethanol precipitation (40-80% v/v), maintaining native conformations essential for enhanced fibroblast proliferation observed in biocompatibility assays (Manjubala *et al.*, 2020; Boraiah and Mallaiah, 2024). Microwave-assisted steam degumming emerges as highly efficient alternative, achieving 28-35% sericin recovery within 5-10 min at 120-140°C using 0.1-0.3 MPa steam pressure, reducing energy consumption by 75% compared to conventional boiling while preserving 85-92% antioxidant activity (Pan *et al.*, 2024). Citric acid extraction (pH 4.0-4.5, 80-90°C for 60-90 min) recovers 32-38% sericin with significantly higher DPPH scavenging (IC_{50} 45.2 µg/ml) and α-amylase inhibition (78.3%) compared to hot water methods (IC_{50} 72.1 µg/ml) offering chemical-free alternative with superior antidiabetic bioactivity (Sincar *et al.*, 2026). Ultrasound-assisted processing (20-40 kHz, 300-500 W at 50-70°C for 20-40 min) utilizes cavitation micro jets to disrupt sericin matrices, attaining 90-99% yields without chemical additives

while preserving molecular integrity, complemented by tangential flow filtration for efficient isolation (Bascou *et al.*, 2022). Membrane ultrafiltration systems (10-100 kDa MWCO) concentrate process liquors to 15-30% solids with 95% salt rejection through diafiltration (3-5 diavolumes), enabling continuous recovery from dilute streams at 80-95% mass efficiency (Gimenes *et al.*, 2014). Autoclaving (121°C, 1-1.5 kgf/cm² for 30-60 min) extracts high molecular weight fractions *via* steam-mediated shear, recoverable through freeze-thaw cycles or isoelectric precipitation (pI 4.0-4.5) yielding lyophilizates comparable to recombinant standards in L929 cell viability (>98% at 5 mg/ml) (Rocha *et al.*, 2017). Alkaline/waste water-derived sericin shows lower molecular weight (<50 kDa), reduced bioactivity and some toxicity, making it suitable for bulk applications after purification. Enzymatic/autoclaved sericin retains native structure (200-400 kDa) with superior cell growth, antioxidant capacity and skin compatibility, ideal for premium cosmeceuticals (Paladini *et al.*, 2025).

4. Multifunctional efficacy in skin and hair care

Sericin revolutionizes cosmeceutical formulations through its distinctive amino acid composition featuring serine (28-33%), glycine (14-19%) and abundant hydroxy residues (46%) across 50-400 kDa fractions that orchestrates concurrent hydration, antioxidant protection and regenerative effects surpassing many synthetic counterparts while embracing clean-label sustainability (Padamwar and Pawar, 2004; Sheng *et al.*, 2013). This natural silk glycoprotein's amphiphilic nature and conformational plasticity enable multi-target efficacy across skin barrier repair, pigmentation control and hair fortification (Zhang, 2002).

4.1 Core moisturizing and film-forming mechanisms

Sericin's humectant superiority originates from its serine dominance (28-33% of total amino acids) coupled with 46% hydrophilic hydroxy residues that establish multilayer hydrogen-bonding cascades within the stratum corneum, binding 2-3 water molecules per functional group far exceeding glycerol's capacity (Padamwar *et al.*, 2005). This molecular architecture mimics the skin's natural moisturizing factor (NMF), directly replenishing corneocyte amino acids while clinical corneometry demonstrates 25-40% capacitance increase over 4 weeks versus 15-20% for standard emollients, with sustained effects persisting 24 h post-application (Polášková *et al.*, 2015).

Mechanistic duality combines intrinsic NMF restoration elevating hydroxyproline content by 18-25% through amino acid supplementation with extrinsic barrier reinforcement. Padamwar *et al.* (2005) documented significant impedance reduction (35 ± 4%) and transepidermal water loss (TEWL) decrease (28-32%) in sericin gels stabilized by pluronic/carbopol, where scanning electron microscopy revealed corneocyte smoothing and reduced desquamation versus untreated dry skin. This reflects sericin's amphiphilic conformational adaptability forming organized β-sheet domains that create semi-permeable films (10-50 µm thick) through cationic-anionic electrostatic pairing with keratin's glutamic/aspartic acid residues (Gholap *et al.*, 2023).

Non-comedogenic advantage stems from sericin's high solubility (>95% at pH 6-8) preventing pore occlusion common with petrolatum (miliaria risk 15-20%), while maintaining oxygen/nutrient diffusion critical for epidermal metabolism. *In vitro* permeation studies confirm 85% film porosity versus 40% for mineral oil, balancing occlusion with active delivery (Polášková *et al.*, 2015).

Hair shaft dynamics mirror skin interactions: Sericin's isoelectric point (pI 6.8-7.2) enables protonated amine groups to neutralize cuticle carboxylate charges, collapsing elevated scales observed in damaged hair (SEM confirmation). This conformal nanocoating reduces frizz index by 40-60% (gravimetric static charge measurement), cuts wet combing force 25% (dynamometer testing) and boosts luster 20-30% through optimized refractive index matching (1.54 vs. hair cortex 1.55) without hydrolytic residue after 10 wash cycles (Gholap *et al.*, 2023). Unlike quaternary ammonium conditioners, sericin's biodegradability eliminates build up while penetrating 20-30% into cortex for internal reinforcement. These validated mechanisms position sericin as a paradigm shift from conventional moisturizers, delivering consumer-perceptible softness with dermatological efficacy across diverse phototypes and hair porosities (Padamwar *et al.*, 2005).

4.2 Antioxidant and anti-pollution activity

Sericin shields skin from oxidative damage through direct radical scavenging and cellular defense activation. This protein combats oxidative stress through phenolic hydroxyl groups on tyrosine residues and metal-chelating sites from aspartic acid and histidine, effectively scavenging DPPH radicals (IC_{50} 0.5-2.0 mg/ml) and superoxide anions generated by urban PM2.5 exposure (Sincar *et al.*, 2026). This direct antioxidant action synergizes with indirect Nrf2/HO-1 pathway activation, boosting endogenous glutathione levels 1.5-2-fold in UVA-irradiated keratinocytes and preventing ROS-mediated apoptosis in dermal fibroblasts (Yang *et al.*, 2023; Manesa *et al.*, 2020). The protein's ability to sequester iron and copper ions inhibits Fenton reactions that amplify pollution-induced lipid peroxidation, maintaining cellular viability above 85% under combined UV-pollutant stress while preserving collagen fibril integrity against advanced glycation end products (Silva *et al.*, 2022).

4.3 Antiageing and wound healing potential

Sericin rejuvenates ageing skin and accelerates tissue repair through matrix remodelling pathways. Sericin promotes dermal matrix remodelling through TGF-β1 upregulation and α5β1 integrin signalling, driving human fibroblasts to elevate collagen I/III production by 1.5-2.2-fold alongside 60-70% MMP-1/9 suppression that preserves extracellular matrix against UV-induced degradation (Mazurek *et al.*, 2024; Kitisin *et al.*, 2013). In full-thickness excisional wound models, sericin hydrogels achieve 80-90% closure by day 14 (versus 60% controls) *via* accelerated keratinocyte migration (35 ìm/day), enhanced VEGF-mediated angiogenesis and organized granulation tissue deposition confirmed by HandE histology (Stradczuk-Mazurek *et al.*, 2025). *In situ* gelling systems provide moist wound environments that reduce healing time by 40% compared to traditional dressings, with robust antibacterial activity preventing biofilm formation (Wang *et al.*, 2024). Clinical translation shows reduced wrinkle depth (15-20%) and elasticity improvement (25%) after 12-week topical use, positioning sericin as a non-invasive antiageing active (Joseph *et al.*, 2024). Silk biomaterials like sericin excel across all healing phases, achieving 95% closure in 21 days for chronic wounds while supporting bioengineered skin grafts (Chouhan and Mandal, 2020)

4.4 Skin brightening and antityrosinase properties

Sericin lightens hyperpigmentation by blocking melanin synthesis at multiple enzymatic levels. Competitive Cu^{2+} chelation by sericin's aspartate/threonine clusters disrupts tyrosinase catalysis (IC_{50} 0.1-

0.5 mg/ml across extraction methods), blocking L-DOPA oxidation and reducing melanin by 30-55% in α-MSH-stimulated B16 cells, with serine-rich motifs providing additional steric occlusion of the enzyme's active site (Aramwit *et al.*, 2010). High molecular weight fractions (>50 kDa) demonstrate superior inhibition due to conformational stability, while 8-week clinical patch tests confirm 15-25% hyperpigmentation reduction across Fitzpatrick types III-V, particularly effective against melasma and post-inflammatory hyperpigmentation (Kanpipit *et al.*, 2022). This multi-mechanism approach outperforms single-target hydroquinone derivatives without cytotoxicity concerns (Gholap *et al.*, 2023).

4.5 Soothing and anti-inflammatory effects

Sericin calms irritated skin by suppressing inflammatory cascades and restoring barrier lipids. NF-Sericin dampens innate immune responses by inhibiting NF-κB p65 nuclear translocation, reducing TNF-α, IL-6 and IL-1β secretion by 45-65% from LPS-challenged macrophages while upregulating ceramide synthase to restore stratum corneum lipid lamellae disrupted in atopic dermatitis (Silva *et al.*, 2022). This dual anti-inflammatory and barrier-repair action resolves irritant contact dermatitis (50% erythema reduction within 48 h), UV-induced erythema and post-procedural inflammation, with clinical studies showing significant pruritus relief in sensitive skin cohorts (Joseph *et al.*, 2024). The protein's biocompatibility enables incorporation in formulations for rosacea, eczema and barrier-compromised skin without steroid dependency (Heryati *et al.*, 2024).

4.6 Hair care benefits

Sericin strengthens and conditions hair through molecular-level cuticle and cortex reinforcement. Sericin's cationic domains (pI 6.8-7.2) at skin pH facilitate cuticle penetration, forming hydrogen bonds with keratin cystine residues to boost tensile strength 20-35% (break load) and Young's modulus (stiffness) while cutting combing force 30-40% through molecular lubrication rivalling silicones (Banerjee *et al.*, 2025). Its refractive index (1.54) precisely matches hair cortex for optimal light scattering, delivering 25-30% gloss enhancement *via* spectrophotometry, while thermal decomposition temperature (Td 240°C) provides heat protection during styling (Qadir and Islam, 2024). Scanning Electron Microscope (SEM) analysis confirms scale realignment and cortex reinforcement in bleached hair with rinse-off after 10 cycles preventing build up while maintaining conditioning efficacy superior to synthetic polypeptides (Hari and Kandasubramanian, 2025).

5. Formulation science and advanced delivery systems

Sericin demonstrates exceptional formulation versatility across conventional cosmetics and cutting-edge delivery systems, leveraging its amphiphilic nature and pH-responsive properties (Joseph *et al.*, 2024; Orlandi *et al.*, 2020).

5.1 Incorporation into cosmetic vehicles

Hydrolyzed sericin with molecular weights of 20-50 kDa at concentrations of 0.5-3% w/w enhances oil-in-water emulsions by adsorbing at interfaces, maintaining physical stability through three months of accelerated testing at 40°C and 75% relative humidity without creaming or coalescence (Orlandi *et al.*, 2020). Sericin also demonstrates superior tyrosinase inhibition and antioxidant capacity compared to regenerated fibroin, confirming its dual role in skin repair and cosmetic whitening applications (Su *et al.*, 2019). Sericin derived from hot water degumming processes outperforms soy lecithin by reducing droplet sizes by 28% (Züge *et al.*, 2017). Kochi silkworm sericin maintains 92% cell viability confirming topical safety (Kwon *et al.*, 2023). It preserves optical clarity and achieves droplet-free formulations suitable for airless packaging, demonstrating 28-day microbial stability (Diona *et al.*, 2025) Hidayat *et al.*, 2022). Carbomer and hectorite gels accommodate 1-2% sericin loading while maintaining pseudoplastic rheology ideal for consumer application. Double-blinded split-face clinical trials of sericin-niacinamide formulations document 22% capacitance improvement and 18% elasticity enhancement versus controls after 28 days, with safety confirmed across 45 product categories at concentrations up to 10% (Berardesca *et al.*, 2015; Johnson *et al.*, 2020).

Film-forming sericin gels crosslinked with genipin or microbial transglutaminase rapidly transition from liquid to elastic solids exhibiting storage moduli of 1500-3000 Pa within five minutes, creating breathable facial treatment barriers (Wongtechanon *et al.*, 2025). Silk sericin/gelatin composite films enhance mechanical elasticity for cosmetic applications (Pankaew *et al.*, 2015). Syndet bars incorporating 5-8% sericin *via* hot-melt extrusion at 65-75°C achieve mild cleansing profiles with zein scores below 120 mg N/100 bars and reduce inter-fiber friction by 32% post-rinse, surpassing sodium lauryl sulfate benchmarks (Shitole *et al.*, 2020). Bacterial nanocellulose-sericin masks deliver sustained hydration over eight hours through controlled protein diffusion (Aramwit and Bang, 2014).

5.2 Synergistic blends and composite materials

Hyaluronic acid-sericin matrices formulated at 1:0.2 ratios create interpenetrating hydrogen-bonded networks that double stratum corneum hydration through complementary molecular weight water-binding capacities, significantly outperforming individual components during 28-day corneometry assessments (Berardesca *et al.*, 2015). Purple waxy corn cob extract-loaded sericin hydrogels demonstrate 35% melanin reduction through tyrosinase inhibition for anti-hyperpigmentation applications (Kanpipit *et al.*, 2022).

Chitosan-sericin polyelectrolyte complexes at pH 5.0 form mucoadhesive films that extend niacinamide release over 72 h compared to 12 h for free actives (Suryawanshi *et al.*, 2020). Silkworm sericin nanoparticles (701 nm) incorporated into 5-10% moisturizing lotions deliver 35% greater hydration than conventional formulas through enhanced skin penetration and film formation (Hidayat *et al.*, 2022). Niacinamide-loaded sericin nanoparticles prepared *via* water-in-silicone techniques enhance skin deposition efficiency (Orachun *et al.*, 2012). Electrospun sericin nanofibers self-assemble into flexible cosmetic films ideal for masks, providing controlled active release through breathable matrices (Dragojlov *et al.*, 2025).

5.3 Advanced delivery platforms

Sericin-chitosan nanoparticles measuring 120-250 nm exhibit pH-responsive charge reversal facilitating follicular penetration, encapsulating retinoids with 82% efficiency and demonstrating zero-order release kinetics over 21 days, harnessing sericin's ability to modulate transcription factors and suppress inflammatory signaling for precise therapeutic delivery (Suryawanshi *et al.*, 2020; Das *et al.*, 2021). Silk sericin-alginate microcapsules provide core-shell protection for hydrophilic actives with optimized burst-sustain release profiles ideal for antiageing serum applications, enhanced by enzyme-extracted sericin uniformity (Shitole *et al.*, 2020; Vaishnav and Singh, 2023).

In situ gelling sericin formulations transition from solution to hydrogel within three minutes at skin pH, enzyme-triggered crosslinking rapidly fills irregular wound shapes while creating moist healing environments that combat oxidative stress through sericin's inherent antioxidant properties (Baptista-Silva *et al*., 2021). Sericin hydrogels enriched with banana peel powder and silver nanoparticles show remarkable wound contraction (86% in 11 days vs 57% commercial control), cutting healing time while reducing inflammation through lower IL-6 and higher IL-10 levels (Munir *et al*., 2023). Bacterial nanocellulose-sericin gel systems confirm controlled eight-hour release characteristics (Aramwit and Bang, 2014). Electrospun sericin nanofiber matrices with 200-400 nm diameters achieve 90% encapsulation efficiency for epidermal growth factor with sequential release profiles, while polymeric scaffolds for acne treatment sustain sericin delivery over 14 days, accelerating inflammation resolution by 45% compared to controls (Vargas González *et al*., 2025). Sericin nanofiber films optimize cosmetic deposition while silk manufacturing waste integration exemplifies circular economy principles (Dragojlov *et al*., 2025; Sorlini and Menato, 2020).

6. Market landscape, commercial trends and regulatory framework

The sericin market demonstrates sustained expansion through cosmeceutical demand, biomedical innovation and sustainability imperatives, supported by established safety profiles across diverse regulatory jurisdictions (Fact.MR, 2025; Johnson *et al*., 2020; Momentum Flow, 2025).

6.1 Global market analysis

Global sericin valuation reaches USD 361.5 million in 2025, projected to attain USD 638.9 million by 2035 at 5.8% CAGR, with cosmetics commanding 65% share and 8.2% growth driven by antioxidant moisturizing benefits (Fact.MR, 2025). Alternative projections cite USD 1.2 billion in 2024 expanding to USD 2.5 billion by 2033 (9.5% CAGR from 2026), alongside Market Glass estimates of USD 350.4 million in 2025 to USD 572.9 million by 2032 (7.3% CAGR), reflecting extraction technology impacts (Market Glass, Inc., 2026; MomentumFlow, 2025; Polaris Market Research, 2023). Sustainability priorities engage 79% of stakeholders, with 65% demanding optimized bioactivity extraction (Fact.MR, 2025; Cognitive Market Research, 2024).

6.2 Segment-wise dynamics

Solid forms lead profitability at 7.6% CAGR through superior stability, preservative reduction and sustainable packaging capturing 45% share in clean beauty powders and bars (Fact.MR, 2025). Cosmetics dominate applications (8.2% CAGR) while biomaterials accelerate *via* drug delivery platforms (Ma *et al*., 2025). The sericin market is segmented into various categories as shown in Table 3.

Table 3: Sericin market segments

Segment	2025 Share	CAGR (2025-2035)	Regional strength
Solid/powder	45%	7.6%	APAC production - China 7.9%, India 7.2% CAGR (Fact.MR, 2025)
Liquid/gel	35%	5.8%	EU premium serums (Cognitive Market Research, 2024)
Cosmetics	65%	8.2%	South Korea 8.1% (Fact.MR, 2025)
Biomaterials	20%	12.5%	North America RandD (Ma *et al*., 2025)

Table 4: Global sericin regulatory framework

Region	Authority	Cosmetic requirements	Biomedical pathway
USA	Food and Drug Administration (FDA)	Voluntary Cosmetic Registration Program (VCRP) notification; Generally Recognized as Safe (GRAS) at ≤5% (Fact.MR, 2025; Johnson *et al*., 2020)	21 CFR biomaterials
EU	REACH/EC 1223/2009 (Registration, Evaluation, Authorisation and Restriction of Chemicals)	COSMOS/ECOCERT organic certification (Fact.MR, 2025)	MDR Class IIa
Korea	Ministry of Food and Drug Safety (MFDS)/ Korea Food and Drug Administration (KFDA)	Functional material registration (Fact.MR, 2025)	Biomedical approval
Japan	Pharmaceuticals and Medical Devices Agency (PMDA)	Quasi-drug functional cosmetics (Fact.MR, 2025)	Excipient validation
China	National Medical Products Administration (NMPA)/ China State Food and Drug Administration (CSAR)	New ingredient registration (Fact.MR, 2025)	CFDA mandatory

6.3 Regulatory panorama

Sericin faces distinct regulatory pathways for cosmetics versus biomedical uses across major regions, balancing innovation with safety standards (Fact.MR, 2025; Johnson *et al*., 2020). Table 4 summarises the global regulatory framework for sericin, highlighting approvals and guidelines in key regions like the US, EU, Japan, Korea and China. Safety panels confirm no adverse effects at typical concentrations across formulations (Johnson et al., 2020)..

6.4 Consumer trends and strategic priorities

Clean beauty propels personal care beyond 8% annual growth *via* sericin's repair properties and waste upcycling, while vegan biomaterials gain traction (Fact.MR, 2025; Banerjee *et al*., 2025).

Enzyme-assisted supercritical extraction cuts costs amid 79% eco-focus, powering wound healing innovations (Ma *et al.*, 2025). Kraig Biocraft Laboratories commands 20-25% share through recombinant scalability; Seiren advances purified cosmetics grades (Fact.MR, 2025). Biotech-cosmetic alliances, COSMOS premiums (25% uplift) and green diversification counter supply risks in sericulture hubs (Momentum Flow, 2025).

7. Challenges and future perspectives

Sericin commercialization navigates technical inconsistencies alongside validation gaps while demonstrating strong growth potential through biomaterials innovation. Market projections indicate USD 638.9 million by 2035, but scale-up barriers and clinical evidence shortages limit full realization (Fact. MR, 2025). Resolution requires integrated green chemistry and dermatological research convergence amid 85% stakeholder supply chain concerns transformative potential demands overcoming these hurdles through strategic innovation.

7.1 Persistent challenges

Production standardization remains primary obstacle due to extraction method variability compromising batch consistency. Alkali processes yield heterogeneous sericin (20-150 kDa polydispersity) while enzymatic methods elevate costs 3x despite superior purity demanded by 65% stakeholders (Kabir *et al.*, 2024; Fact.MR, 2025). Dose-dependent cytotoxicity above 2 mg/ml reduces fibroblast viability to 65% at 72 h exposure, challenging biomedical scalability beyond cosmetic safety limits (Öksüz, 2025; Johnson *et al.*, 2020). Addressing these technical-economic barriers through standardized protocols and cost-optimized extraction remains essential for market competitiveness.

7.2 Emerging research frontiers

Recent technological breakthroughs are redefining sericin's commercial viability across cosmetics and regenerative medicine applications. Recombinant engineering eliminates silk dependency producing uniform 50-70 kDa sericin for scalable drug delivery. Platforms achieve 95% encapsulation efficiency with sustained release matching wound healing kinetics validated through HUVEC assays (Xia *et al.*, 2026; Ma *et al.*, 2025). Nanostructured cosmeceuticals (120 nm particles) demonstrate 50% tyrosinase inhibition and 24 hour TEWL reduction in 3D skin equivalents, while sericin-chitosan hybrids yield 85% cell adhesion for COSMOS-compliant scaffolds (Veiga *et al.*, 2024). These innovations position sericin at clean beauty and regenerative medicine convergence, requiring clinical translation for commercial breakthrough.

8. Conclusion

Sericin has transcended its origins as a silk industry waste stream to become a definitive model for the circular economy within the cosmeceutical and biomedical sectors. Technically, the protein's value is predicated on its remarkable versatility as a bioactive ingredient specifically its antioxidant, moisturizing, and film-forming properties which allow for seamless integration into diverse delivery systems. From stable emulsions to pH-responsive nanoparticles and electrospun scaffolds, sericin's formulation adaptability is further enhanced by advanced biochemical modifications such as enzymatic hydrolysis and targeted cross-linking. These high-precision platforms currently achieve superior drug encapsulation efficiency and include innovations such as nano-encapsulated particles demonstrating potent tyrosinase inhibition. While challenges regarding batch-to-batch variability, cytotoxicity thresholds (*e.g.,* 2 mg/ml) due to the degradative impact of traditional thermo-chemical degumming compared to enzymatic methods, a deficit in Phase II clinical validation remain and the development of high-performance protein composites that meet international organic safety standards (COSMOS) underscores a clear trajectory toward clinical and regenerative applications.

This technical maturity directly fuels sericin's escalating economic profile, particularly within a cosmetics market that now commands a 65% share of the sector and a projected 8.2% CAGR through 2035. The ascent of sericin as a premium bioactive ingredient is increasingly supported by strategic biotech alliances, which already secure 20-25% of the recombinant market share, reflecting a broader 79% industry emphasis on sustainability. To fully realize this potential, an orchestrated interdisciplinary effort is required to standardize extraction *via* green chemistry, conduct rigorous dermatological trials and harmonize regulatory frameworks across the FDA, REACH, and MFDS. Ultimately, sericin represents more than a natural active; it is a blueprint for converting agricultural by-products into high-value essentials through the confluence of science, ingenuity and purposeful market strategy.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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