ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2026): 4.97
IJAFS 2026; 8(5): 33-39
www.agriculturaljournals.com
Received: 23-02-2026
Accepted: 27-03-2026

Ishfaq Ahmad Malla
College of Temperate Sericulture, Mirgund, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Sumaira Aslam Malik
College of Temperate Sericulture, Mirgund, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Corresponding Author:
Ishfaq Ahmad Malla
College of Temperate Sericulture, Mirgund, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Silk fibroin and silver nanoparticle-based nanocomposites: Structure, processing, and emerging biomedical applications: A comprehensive review

Ishfaq Ahmad Malla and Sumaira Aslam Malik

DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i5a.1484

Abstract
Fibroin, a natural structural protein derived primarily from Bombyx mori, has emerged as a versatile biomaterial due to its unique combination of biocompatibility, biodegradability, mechanical strength, and tunable structural properties. Its hierarchical organization, consisting of β-sheet crystalline domains interspersed with amorphous regions, provides remarkable stability and functional adaptability. Recent advancements in nanotechnology have further expanded the utility of silk fibroin through the development of fibroin-based nanoparticles and nanocomposites, particularly with silver nanoparticles (AgNPs). These hybrid systems exhibit enhanced physicochemical and biological properties, including superior antimicrobial, antioxidant, and therapeutic potential. Various fabrication techniques such as electrospinning, electro spraying, solvent-induced precipitation, and supercritical fluid processing have enabled the controlled synthesis of silk fibroin nanoparticles with tailored size, morphology, and functionality. Moreover, silk fibroin serves as an efficient stabilizing and reducing agent in the green synthesis of AgNPs, overcoming issues related to nanoparticle aggregation and oxidation. The integration of AgNPs into silk fibroin matrices has demonstrated significant efficacy against pathogenic microorganisms, biofilm inhibition, and potential applications in wound healing, drug delivery, tissue engineering, and biomedical devices. This review comprehensively summarizes the structural characteristics, extraction and processing methods, nanoparticle fabrication strategies, and multifunctional applications of silk fibroin and its nanocomposites. It also highlights recent developments and future prospects in the field, emphasizing the growing importance of sustainable and biocompatible materials in advanced biomedical and technological applications.

Keywords: Fibroin, biomaterials, morphology, crystalline, tissue

Introduction
Silkworms are reared for the production of silk fiber which has an aesthetic appeal due to its luster, shine and softness apart from other properties, *viz*, strength, absorbency, thermal regulation, light weight as compared to other natural and synthetic fabrics. India is the second-largest producer of raw silk after China with annual raw silk production 41,121 MT with 31,119 MT of Mulberry, 7886 MT of eri, 1884 MT of tasar and 232 MT of muga and the raw silk production of jammu and Kashmir was 116 MT (Anonymous, 2025) [1]. Silk fibroin is a structural protein, like collagen, but with a unique feature it is produced from the extrusion of an amino-acidic suspension by a living complex organism (while collagen is produced in the extra-cellular space by self-assembly of cell-produced monomers). Silk fibroin properties are derived from its structure, which consists of hydrophobic blocks staggered by hydrophilic, acidic spacers (Jin and Kaplan 2003) [14]. In its natural state, silk fibroin is organized in beta-sheet crystals alternated by amorphous regions, which provide strength and resilience to the protein. The multiplicities of forms in which regenerated silk fibroin can be processed at a high protein concentration and molecular weight make it attractive for several high-tech applications, as recently reported (Huang 2023) [13]. Nano-sized particles are basically small objects that act as a whole unit in accordance with their transport and properties. Fine particles have the range of 100-2500nm and ultrafine particles have the size of 1- 100nm (Pandey and Khuller 2006) [23]. They can also be designed to improve the pharmacological and therapeutic effects of the drugs. They also have a very high surface area and they permit many functional groups to be adhered to them which in turn,

can bind to tumor cells. They have proven to be an excellent replacement for radiation and chemotherapy as they can easily assemble in the micro-environment of the tumor (Zheng *et al* 2015) [44]. Silver nanoparticles (AgNPs) are well-known for their anti-bacterial property to a broad spectrum of bacteria and have been used increasingly in detergents, plastics, food storage containers, antiseptic sprays, catheters, bandages, and textiles, and so forth. Nevertheless, practical applications of AgNPs are often hampered by their easy oxidization weakness, which may cause the loss of the anti-bacterial activity. To overcome this problem, different organic and inorganic templates have been employed to stabilize AgNPs through the formation of nano-composites *(*Kumar and Helmut*,* 2005) [16]. Silk fibroin is also a good candidate for a soluble template for bio-mineralization. Despite significant advancements in silk fibroin and silver nanoparticle research, a comprehensive understanding of their combined potential and processing strategies remains limited. Therefore, this review aims to critically analyze existing studies and highlight recent developments, challenges, and future prospects of silk fibroin-based nanocomposites for biomedical and technological applications."

Progress and Developments in Silk Fibroin Research

Sasaki and Noda (1973) [31] conducted a study on silk fibroin of *Bombyx mori* directly extracted from the silk gland. The weight-average molecular weight of fibroin, directly extracted from the posterior portion of the middle silk gland of *B. mori*, was determined under specific conditions using 6 M guanidine HCl or 8 M urea solution at pH 7.0. This analysis provided an accurate measurement of the molecular weight, offering insights into the structural properties of fibroin in its native state.

Gage and Manning (1980) [9] conducted a study on Internal structure of the silk fibroin gene of *B. mori*. The organization of the DNA sequence encoding the silk fibroin gene in *B.mori* was analyzed, revealing both polymorphic and invariant features. While the total gene length, protein size, and restriction site patterns vary significantly among inbred stocks, certain structural features remain consistent across alleles. Fibroin is primarily composed of alternating "crystalline" and "amorphous" peptides of known sequence, though their precise arrangement in the protein is unclear. Analysis revealed that the repetitive core of the gene (about 15 kilobases) is organized into at least 10 large crystalline coding domains interrupted by smaller amorphous domains

Tsukada *et al.,* (1994) [37] conducted a study for the preparation and morphological characterization of porous materials obtained by freezing and lyophilizing silk fibroin solutions. When an aqueous silk solution is frozen at different temperatures (−18, −45, and −80°C), the average pore size decreases with lowering of the freezing temperature. Silk fibroin aggregates obtained in these conditions exhibit a sheetlike structure. By lowering the pH from neutrality to 4.01 and 2.65, the morphology of the solid phase changes from a sheet to a fiber structure. The addition of different amounts of methanol to the silk solution results in a sharp fall of the average pore size and hardens the material, as a consequence of the high packing density of the fibroin molecules. Silk fibroin aggregates prepared in these conditions exhibit a typical fibrous structure.

Zhou *et al.,* (2001) [45] conducted a study on Silk fibroin: structural implications of a remarkable amino acid sequence. The amino acid sequence of the heavy chain of *B.mori* silk fibroin was determined from its gene sequence, revealing a 5,263-residue (391-kDa) polypeptide chain. This chain consists predominantly (94%) of 12 low-complexity "crystalline" domains formed by Gly-X repeats, where X is Ala in 65%, Ser in 23%, and Tyr in 9% of the repeats. The remaining sequence includes a nonrepetitive 151-residue N-terminal header, 11 nearly identical 43-residue spacer sequences, and a 58-residue C-terminal segment. The strict alternation of Gly-X residues supports the classic Pauling-Corey β-sheet model, where β-sheets pack in alternating Gly/Gly and X/X layers. Based on the actual sequence, it is proposed that each subdomain forms a β-strand, while each crystalline domain forms a two-layered β-sandwich.

Sashina *et al*., (2006) [32] in their study have reported that the resulting fibroin is termed regenerated silk fibroin. An appropriate solvent system, such as lithium bromide aqueous solution, Ajisawa's reagent (calcium chloride: ethanol: water with 1:8:2 molar ratio), lithium thiocyanate aqueous solution, calcium nitrate aqueous solution, *N*-methyl morpholine-*N* oxide, hexa fluoro isopropanol (HFIP), or ionic liquids, is used to dissolve SF. Each solvent system presents different solubility power, and thus they require different dissolving times and temperatures.

Gulrajani *et al*., (2007) [12] have reported that the Silk fabrics treated with 40 ppm silver hydrosol produced at 5ºC and 60 ppm silver hydrosol produced at 40ºC showed 100% antimicrobial activity against the gram-positive bacterium *Staphylococcus aureus.*

Zhang *et al*., (2007) [41] conducted a study on the formation of silk fibroin nanoparticles in water-miscible organic solvents and their characterization. Silk fibroin nanoparticles were rapidly prepared from liquid silk using water-miscible protonic and polar aprotic organic solvents. These nanoparticles are insoluble but remain well-dispersed and stable in aqueous solutions. Characterized as globular particles, their sizes range from 35 to 125 nm in diameter, as determined by TEM, SEM, AFM, and laser sizing techniques.

Cao *et al.,* (2007) [4] reported that the Silk fibroin microspheres/ nanoparticles, which are useful for drug,protein,gene intravenous delivery systems, can be generated using the self-assembly method, lipid-based emulsifiers, or polymer co-carriers. First, SF micelles can be self-assembled via the arrangement of hydrophilic and hydrophobic chain segments of the SF molecules when ethanol is added to them, followed by quenching below their freezing point.

Mondal *et al.,* (2007) [20] conducted a study on the extraction of liquid and powder fibroin from the cocoon shells of the silkworm *B. mori* L. The degummed fibers from different breeds and hybrids of *B. mori* were dissolved in varying ratios using dissolving solutions I, II, and III. These degummed fibers, along with the dissolving solutions, were maintained at a temperature of 55 ºC for durations ranging from 15 to 180 minutes. The degummed fibers from all breeds and hybrids completely dissolved in solution I at 55 ºC within 1 hour.

Myung *et al*. (2008) [21] conducted a study on fluorescent silk fibroin nanoparticles prepared using a reverse microemulsion method. Color dye-doped silk fibroin nanoparticles were successfully fabricated using a

microemulsion method. Silk fibroin solution was prepared by dissolving *B.mori* cocoons in concentrated lithium bromide, followed by dialysis to remove impurities. A color dye solution was then mixed with the silk fibroin solution, and surfactants used in the microemulsion were removed using methanol and ethanol. This process yielded dye-doped silk fibroin nanoparticles with an average diameter of approximately 167 nm. The nanoparticles' morphology was analyzed using field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM), while their size and distribution were measured by dynamic light scattering (DLS). Confocal laser scanning microscopy confirmed the successful incorporation of the dye into the nanoparticles.

Grinia *et al*., (2010) reported that the secondary structure of silk fibroin on dense membranes was either random coil (silk I) or b-sheet (silk II), before and after ethanol treatment, respectively. The sterilized membranes presented no cytotoxicity to endothelial cells during *in vitro* assays. This fact stresses the material potential to be used in the fabrication of biomaterials, as coatings of cardiovascular devices and as membranes for wound dressing or drug delivery systems.

Sah *et al*., (2010) [28] reported that the raw silk cocoon must first undergo degumming to eliminate sericin. Therefore, these cocoons are boiled in a diluted solution of sodium carbonate (Na_2CO_3) followed by rinsing and washing with pure water and overnight drying to obtain fibroin filaments. The boiling time and Na_2CO_3 concentration should be well controlled to prevent any negative effects this process might have on the resulting fibroin.

Sah and Pramanik (2010) [28] conducted study to prepare silk fibroin solution for possible applications in tissue engineering. Pure silk fibroin protein was extracted from *B. mori* silk cocoon by degumming method using aqueous Na_2CO_3 solution followed by solubilizing in LiBr aqueous solution. The fibroin protein solution was purified and studied for the protein content. The morphology of degummed silk were investigated by scanning electronic microscopy (SEM) at different magnification. SEM revealed the absence of glue like sericine over the silk fibroin surface at optimal degumming condition. The fibroin protein content of the solution was measured by Bradford protein assay. The results indicate that the regenerated silk fibroin (RSF) can be used for fabrication of porous silk fibroin scaffolds for various tissue engineering applications.

Rockwood *et al*., (2011) [26] reported that the variety of aqueous or organic solvent-processing methods can be used to generate silk biomaterials for a range of applications. These methods facilitate extraction of silk bio-materials from *B.mori* cocoons to fabricate hydrogels, tubes, sponges, composites, fibers, microspheres and thin films. These materials can be used directly as biomaterials for implants, as scaffolding in tissue engineering and *in vitro* disease models, as well as for drug delivery. It was also reported that the electrolytes are typically removed via dialysis against pure water, and aqueous solutions of fibroin are obtained. An aqueous solution of polyethylene glycol (PEG) 20 wt% could be used instead of pure water to obtain more concentrated fibroin solution. Depending on its concentration, the fibroin solution obtained after dialysis could be stored at 4° _C for months or at room temperature for weeks.

Gholami *et al*., (2011) [10] conducted a study on the Production of fibroin nanopowder through electrospraying. Various methods were employed to produce fibroin powder with different particle size ranges, but this study introduces a novel application of the electrospraying technique for generating fibroin nanopowder. The process involves electrospraying a dilute fibroin solution in formic acid, and the effects of key variables—such as fibroin concentration, voltage, feed rate, and needle-to-collector distance—on the average particle size were examined. The results showed that electrospraying can produce fibroin nanopowder with an average particle size as small as 80 nm, making it one of the most effective methods, alongside precipitation techniques, for achieving such small particle sizes. However, nanopowder produced via electrospraying is more uniform in spherical shape and size. It was found that lower concentrations, lower feed rates, and longer needle-to-collector distances reduce particle size. Additionally, increasing voltage up to 20 kV decreases the particle size, but higher voltages result in an increase.

Wray *et al*., (2011) [39] reported that the high Na_2CO_3 concentration and prolonged boiling time could lead to the cleavage of the disulfide bonds between H- and L-fibroin and the fragmentation of the amorphous sequences could generate fibroin of poly dispersed molecular weight.

Fan *et al*. (2012) [7] conducted a study on Vitamin C-reinforcing silk fibroin nanofibrous matrices for skin care application.This study presents the preparation and evaluation of L-ascorbic acid 2-phosphate (VC-2-p)-loaded silk fibroin (SF) nanofibrous matrices, fabricated for the first time using an eco-friendly electrospinning process. A post-treatment with 75% ethanol vapor transformed the unstable silk I structure into a water-stable silk II form. *In vitro* release studies demonstrated that VC-2-p was easily released from the SF nanofibrous matrices. Both neat and VC-2-p-loaded SF matrices supported the adhesion, spreading, and proliferation of L929 mouse fibroblast cells. Notably, compared to neat SF matrices, VC-2-p-loaded SF matrices significantly enhanced the expression of collagen type I alpha 1 (Col1a1), as confirmed by real-time PCR. Further studies using an oxidative injury model revealed that both matrices protected L929 cells from tert-butyl hydroperoxide-induced oxidative stress through antioxidative mechanisms. Under severe oxidative stress, cells on VC-2-p-loaded matrices maintained higher mRNA levels of Col1a1, glutathione peroxidase 1, and catalase compared to neat SF matrices. These findings highlight the enhanced skin benefits of VC-2-p-loaded SF nanofibrous matrices, showcasing their potential applications in skin care, wound healing, and anti-aging treatments.

Fei *et al*., (2013) [8] reported that the silk fibroin-silver nanoparticle composite shows an effective antibacterial activity against the methicillin-resistant *Staphylcoccus aureus* and subsequently inhibits the biofilm formation caused by the same bacterium. Moreover, a maturely formed biofilm created by methicillin-resistant *S. aureus* can be destroyed by the silk fibroin-silver nanoparticle composite, which meets the demand of clinical application.

Liu *et al*., (2013) [17] conducted a study on extraction and characterization of silk fibroin from waste silk. Waste silk fibers were dissolved in an aqueous calcium chloride solution to investigate the effect of calcium chloride concentration on silk solubility. The dissolved silk fibroin was purified using the dialysis method and subsequently

characterized using Fourier transform infrared spectroscopy (FTIR) and thermoanalysis techniques. The results revealed that the purified silk fibroin predominantly exhibited an irregular curly conformation. Purification significantly improved the thermal properties of the silk fibroin, as evidenced by an increase in the glass transition temperature from 78.9°C-135°C to 90.6°C-135°C. Additionally, the temperature at which 50% thermal weight loss occurred increased from 429.7°C to 490.3°C, demonstrating enhanced thermal stability after purification.

Zhao *et al*., (2013) [42] conducted a study on the generation of silk fibroin nanoparticles via solution-enhanced dispersion by supercritical CO2. Silk fibroin (SF) nanoparticles were successfully prepared using Solution-Enhanced Dispersion by Supercritical CO_2 (SEDS). The experiment demonstrated that SF nanoparticles with particle sizes ranging from 52.5 to 102.3 nm and particle size distributions (PSD) between 0.32 and 0.66 could be fabricated. It was observed that reducing precipitation pressure or increasing the concentration of the SF solution, its flow rate, or the precipitation temperature led to an increase in both particle size and PSD. The mechanism of nanoparticle formation was explained by the formation and growth of SF nuclei within the gaseous miscible phase, which evolved from initial droplets generated by liquid-liquid phase separation. Mass transfer between supercritical CO_2 and the SF solution, combined with supersaturation, was identified as the key process parameter influencing nanoparticle formation.

Çalamak *et al. (*2014) [3] conducted a study on Silk fibroin based antibacterial bio nanotextiles as wound dressing materials. In this study, antibacterial polyethylenimine (PEI) at concentrations of 10%, 20%, and 30% (w/w) was blended with silk fibroin (SF) to successfully fabricate bionanotextiles via electrospinning. Additionally, silk fibroin nanofibers were functionalized with sulfate groups to evaluate their potential antibacterial activity. The resulting fibroin-based bionanotextiles were thoroughly characterized using scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (ATR-FTIR), differential scanning calorimetry (DSC), and thermogravimetric analysis (TGA). Cytotoxicity assessments were performed on L929 fibroblasts using the MTT assay, with results indicating that all fibroin and PEI/fibroin extracts were non-cytotoxic to the L929 cell line. Importantly, the PEI/fibroin bionanotextiles exhibited strong antibacterial activity against both gram-positive *Staphylococcus aureus* and gram-negative *Pseudomonas aeruginosa*, demonstrating their potential as effective antibacterial materials.

Sheng *et al*. (2014) [34] evaluated the one-step synthesis of biocompatible magnetite/silk fibroin core-shell nanoparticles. A one-step hydrothermal process was developed to synthesize core-shell magnetite/silk fibroin (SF) nanoparticles using SF nanofibers as both the template and coating. By increasing the SF content in the reaction system, the Fe_3O_4 nanoparticles aggregated into nanospheres, with sizes ranging from 120 to 500 nm. The magnetic properties, biocompatibility, and functionalization of the Fe_3O_4/SF nanoparticles with antibodies were analyzed, highlighting their potential applications in MRI and bio-separation. This one-step method offers a simpler and more cost-effective alternative to traditional two-step processes for producing biocompatible core-shell magnetite nanoparticles.

Zhang *et al.,* (2014) [40] reported that the inhibition zone test and the antibacterial rate demonstrated that the finished fabrics have an excellent antibacterial property against *Staphylococcus aureus* and *Escherichia coli*. Moreover, the nano silver-treated silk fabrics were laundered 0, 5, 10, 20, and 50 times and still retained the exceptional antibacterial property. When the treated fabrics were washed 50 times, the antibacterial rate is more than 97.43% for S. aureus and 99.86% for *E. coli*.

Pereira *et al*., (2015) [24] reported that the most commonly utilized strategy for the preparation of silk-based materials is the dissolution of silk fibroin threads in pure fibroin solution followed by the regeneration of SF into various material.

Panayotov and Gancheva (2015) [22] Conducted a study to analyse the fibroin content in raw silk threads from *B.mori* cocoons exhibiting different fluorescence characteristics (violet, intermediate, and yellow). A total of 1998 skeins, differentiated by sex and fluorescence of double- and tetra-cross silkworm hybrids, were examined. The results revealed that ultraviolet fluorescence in cocoons affects the fibroin content, with violet fluorescent cocoons showing the lowest content and yellow fluorescent cocoons the highest. Additionally, double-cross hybrids produced skeins with higher fibroin content compared to tetra-cross hybrids. These findings suggest that, for efficient silk reeling, cocoons with yellow fluorescence and double-cross hybrids are more advantageous.

Marelli *et al*. (2016) [19] conducted a study on silk fibroin as an edible coating for the preservation of perishable foods. This study highlights the innovative use of silk fibroin's unique properties—such as polymorphism, conformability, and hydrophobicity—to develop a water-based protein suspension that self-assembles into thin membranes on food surfaces through dip coating. By controlling the protein's polymorphism during post-processing, the permeability of gases like oxygen (O_2), carbon dioxide (CO_2), and water vapor through the silk fibroin films can be modulated, which is crucial for preserving food freshness. Notably, an increase in beta-sheet content within the films leads to reduced oxygen diffusion. Using strawberries and bananas as test cases, the study demonstrates that silk fibroin membranes, only micrometers thick, effectively regulate postharvest fruit physiology by lowering respiration rates and minimizing water loss. This results in a significant extension of fruit shelf life under room conditions, offering a promising approach to food preservation.

Zheng *et al* 2016 [43] conducted a study on Lithium-free processing of silk fibroin. Silk fibroin protein was purified from *B.mori silkworm* cocoons using a novel dialysis strategy to avoid fibroin aggregation and pre-mature formation of β-sheets. The degummed silk fibers were dissolved in Ajisawa's reagent, a mixture of $CaCl_2$-EtOH-H_2O, that is less expensive than lithium bromide. The dissolved solutions were dialyzed against either water or urea solution with a stepwise decrease in concentration. When the steps of 4 M-2 M-1 M-0 M urea (referred to as silk-TS-4210) were adopted, the purified silk fibroin had smaller aggregates (<10 nm), similar average molecular weight (225 kDa) and a lower content of β-sheet (~15%) compared to the sample processing methods (silk-TS-210, 10, 0) studied here. This outcome was close to the fibroin purified by the lithium bromide (silk-Li-0) method

Chirila *et al.,* (2017) [5] reported that the silk fibroin hydrogel can be generated using various chemical reactions

of functionalized silk-based and other precursors, depending on the specific design. The most commonly used cross-linking approach is the enzyme-catalyzed reaction of the Tyr groups of the fibroin chain using hydrogen peroxide and horseradish peroxidase (HRP).

Sharma *et al*., (2018) [33] reported that the solubilization of fibroin extracted from *Antheraea assamensis* (muga) silkworm and *Philosamia ricini* (eri) silkworm using non conventional methods to obtain silk fibroin which could be utilised as biomedical resources. silk fibroin protein was extracted from *P.ricini* and *A.assamensis* silk cocoon by degumming method using aqueous Na_2CO_3 solution.

Saraswathy *et al*., (2018) [30] reported that the release of silver nano-particles from chitosan film depends on dissolution of the AgNPs. Antimicrobial efficacy of the chitosan- PEO- SF film with AgNPs was comparatively studied against two wound colonizing pathogens such as *B.subtilis* and *P.aerugenosa* and it showed significant reduction in cell density.

Augusto *et al*., (2019) [2] reported that the MTT test revealed that silk fibroin hydrogels had low cytotoxicity in THP-1 and HEK-293 cells, whereas the agarose hydrogels showed high toxicity for the THP-1 cell line. The results indicate that silk fibroin hydrogels obtained from a Colombian silkworm hybrid are suitable for the development of scaffolds, with potential applications in tissue engineering.

Holland *et al*., (2019) reported that the silk fabrics for the treatment of dermatological conditions, silk surgical mesh for abdominal wall reconstruction

and investigative plastic surgery applications, and also human clinical trials of SF film for wound healing or tympanic membrane perforation repairs.

Pham and Tiyaboonchai, (2020) [25] reported that the fibroin, especially FNPs, (fibroin nano particles) has a great tendency to be a delivery system of choice for various therapeutic agents including small molecule drugs, protein drugs, genes, and vaccines. Numerous FNP administration routes have been investigated such as parenteral, oral, transdermal, ocular, local bone implantation, and respiratory. Due to the FNP favorable properties, further studies should be focused on the less investigated yet potential routes, namely ocular and respiratory. Finally, yet importantly, most studies on FNPs are based *in vitro* and *in vivo* experiments.

Vidya and Senthilkumar *et al*., (2021) [38] reported that the Silk fibroin has been known to induce wound healing by increasing cell proliferation and growth and migrating various types of cells which are involved in different stages of wound healing process. With several silk varieties like silkworm fibroin, silk sericin, recombinant silk materials, and native spider silk have been investigated for its wound healing applications over the last several decades. This review gives a detailed insight into the structure, general properties, fibroin structure-properties relationship, and biomedical applications of silk fibroin.

Singh *et al*., (2023) reported that the antibacterial study confirmed that SF hydrogel has a moderate antibacterial activity for *Streptococcus mutans,* and *Salmonella typhi.* Additionally, the SRB assay test showed that silk fibroin hydrogels had moderate anticancer activity against the human lung cancer cell line (A549).

Shivananda *et al*., (2023) [35] conducted a study on Preparation and characterization of conducting silk fibroin by Ag nanocoating for electrical applications This study presents the fabrication of eco-friendly silk fibroin (SF)-based biomaterials decorated with silver nanoparticles (AgNPs) to reduce reliance on synthetic materials and minimize environmental hazards. SF acts as a natural reducing and stabilizing agent, converting Ag^+ into neutral Ag^0 under light irradiation. The resulting SF-AgNP nanocomposites, with an average particle size of 35-40 nm, were characterized using XRD, TGA, DSC, SEM, and conductivity studies to analyze their structural, thermal, and electrical properties. The incorporation of AgNPs enhanced SF's electrical and thermal stability, making it suitable for wearable electronics and biomedical applications.

Su *et al*., (2023) [36] conducted a study on the evaluation and application of silk fibroin-based biomaterials for promoting cartilage regeneration in osteoarthritis therapy. Silk fibroin (SF) biomaterials have emerged as promising candidates for cartilage regeneration, thanks to their ability to mimic the fibrous structure and biological activity of collagen. These biomaterials promote chondrocyte proliferation and differentiation, facilitating the formation of new cartilage tissue. With excellent biocompatibility and biodegradability, SF biomaterials are gradually absorbed and metabolized by the human body, ensuring their safety and efficacy. Recent studies have demonstrated their significant potential in treating osteoarthritis (OA), showing encouraging clinical outcomes. As a result, SF biomaterials hold great promise as an effective treatment option for cartilage regeneration and repair in OA patients. This article provides a comprehensive overview of the biological properties of SF, its applications in bone and cartilage injuries, and its clinical prospects, offering valuable insights and references for advancing the field of bone and cartilage repair

Rodrigues *et al.* (2024) [27] conducted a study on Production and Characterization of Silk Fibroin-Aloe vera Hydrogel The study focused on the production and characterization of a silk fibroin (SF) hydrogel incorporating Aloe vera (AV) extract. Four extraction methods—ultrasound-assisted extraction (using bath and probe), stirring, and Soxhlet—were evaluated to determine extraction yield and antioxidant capacity. The hydrogel was produced using a one-step freeze-thaw method and characterized through scanning electron microscopy and Fourier transform infrared spectroscopy. Key properties such as rheological behavior, swelling capacity, and water uptake were analyzed. Release tests of the SF-AV hydrogel were conducted, and the data were mathematically modeled. The hydrogels demonstrated desirable characteristics, including malleability, water insolubility, interconnected pores, and strong thermal and physical stability, making them promising for applications requiring sustained release and durable performance.

Elsaffany *et al.,* (2025) [6] reported that the study successfully demonstrates the biosynthesis of silver nanoparticles (AgNPs) using *B.mori* cocoon extract. The AgNPs exhibited significant antibacterial, antioxidant, anti-inflammatory, and cytotoxic properties, highlighting their potential for various biomedical applications.

Kaewpirom *et al.,* (2025) [15] conducted the study explores the impact of dietary supplementation with probiotics and paraprobiotics on the structural properties of silk fibroin films derived from *Bombyx mori* silkworms. The findings demonstrate that supplementation influences the film-forming properties, crystallinity, and secondary structure of silk fibroin.

Madhukumar *et al*., (2025) [18] reported that the study demonstrates a rapid and eco-friendly method for synthesizing silver nanoparticles (AgNPs) using *Bombyx mori* silk fibroin and UV irradiation. The approach offers a controlled synthesis process, resulting in stable AgNPs with potential applications in medicine, environmental protection, and nanotechnology.

Conclusion

Silk fibroin has established itself as a highly promising biomaterial due to its exceptional structural, mechanical, and biological properties. The ability to process silk fibroin into diverse formats such as films, hydrogels, nanoparticles, and scaffolds has significantly broadened its applicability across multiple disciplines, particularly in biomedicine and nanotechnology. The incorporation of silver nanoparticles into silk fibroin matrices has further enhanced its functional capabilities, especially in terms of antimicrobial and therapeutic efficiency.

Advancements in fabrication techniques, including eco-friendly and green synthesis approaches, have enabled precise control over nanoparticle size, morphology, and stability, thereby improving performance and reducing toxicity concerns. Silk fibroin not only acts as a structural matrix but also as a stabilizing and reducing agent, making it an ideal candidate for the development of sustainable nanocomposites. The reviewed studies demonstrate the effectiveness of silk fibroin-based materials in applications such as drug delivery, wound healing, tissue engineering, food preservation, and antimicrobial textiles.

Despite these advancements, challenges remain in scaling up production, ensuring long-term stability, and translating laboratory findings into clinical and industrial applications. Future research should focus on optimizing synthesis methods, exploring novel functionalizations, and conducting extensive *in vivo* and clinical studies to fully realize the potential of silk fibroin nanocomposites. Overall, silk fibroin combined with nanotechnology represents a powerful platform for developing next-generation biomaterials with wide-ranging applications in healthcare and beyond.

References

1. Anonymous. Seri-states of India 2025 - a profile. New Delhi: Central Silk Board, Ministry of Textiles, Government of India; 2025. p. 1-47.
2. Augusto ZV, Diego FC, Robison BS, Juan FS, Enrique AF, Juan C, *et al*. Silk fibroin hydrogels from the Colombian silkworm *Bombyx mori* L: Evaluation of physicochemical properties. PLoS ONE. 2019;14(3):e0213303.
3. Çalamak S, Erdoğdu C, Özalp M, Ulubayram K. Silk fibroin based antibacterial bio nanotextiles as wound dressing materials. Mater Science Engineering C. 2014;43:11-20.
4. Cao Z, Chen X, Yao J, Huang L, Shao Z. The preparation of regenerated silk fibroin microspheres. Soft Matter. 2007;3:910-915.
5. Chirila TV, Suzuki S, Papolla C. A comparative investigation of *Bombyx mori* silk fibroin hydrogels generated by chemical and enzymatic cross-linking. Biotechnology and Applied Biochemistry. 2017;64:771-781.
6. Elsaffany AH, Abdelaziz AE, Zahra AA, Mekky AE. Green synthesis of silver nanoparticles using cocoon extract of *Bombyx mori* L.: therapeutic potential in antibacterial, antioxidant, anti-inflammatory, and anti-tumor applications. BMC Biotechnology. 2025;25(1):38.
7. Fan L, Wang H, Zhang K, Cai Z, He C, Sheng X, *et al*. Vitamin C-reinforcing silk fibroin nanofibrous matrices for skin care application. RSC Advances. 2012;2(10):4110-4119.
8. Fei X, Jia M, Du X, Yang Y, Zhang R, Shao Z, *et al*. Green synthesis of silk fibroin-silver nanoparticle composites with effective antibacterial and biofilm-disrupting properties. Biomacromolecules. 2013;14(12):4483-4488.
9. Gage LP, Manning RF. Internal structure of the silk fibroin gene of *Bombyx mori* L. The fibroin gene consists of a homogeneous alternating array of repetitious crystalline and amorphous coding sequences. Journal of Biological Chemistry. 1980;255(19):9444-9450.
10. Gholami A, Tavanai H, Moradi AR. Production of fibroin nanopowder through electrospraying. Journal of Nanoparticle Research. 2011;13:2089-2098.
11. Grínia MN, Andrea CD, Carlos AP, Carlos LG, Olga ZH, Bronislaw P, *et al*. Preparation and characterization of ethanol-treated silk fibroin dense membranes for biomaterials application using waste silk fibers as raw material. Bioresource Technology. 2010;101:8446-8451.
12. Gulrajani ML, Deepti GS, Muthu SG. Application of silver nanoparticles on silk for imparting antimicrobial properties. Journal of Applied Polymer Science. 2007;108:614-623.
13. Huang L, Shi J, Zhou W, Zhang Q. Advances in preparation and properties of regenerated silk fibroin. International Journal of Molecular Sciences. 2023;24(17):13153.
14. Jin HJ, Kaplan DL. Mechanism of silk processing in insects and spiders. Nature. 2003;424:1057-1061. https://doi.org/10.1038/nature01809
15. Kaewpirom S, Teangtam W, Monthatong M, Boonsang S. Modification of silk fibroin film structure: From silkworm diet to material properties. International Journal of Biological Macromolecules. 2025:144855.
16. Kumar R, Helmut M. Silver ion release from antimicrobial polyamide/silver composites. Biomaterials. 2005;26:2081-2088.
17. Liu H, Wei J, Zheng LJ, Zhao YP. Extraction and characterization of silk fibroin from waste silk. Advanced Materials Research. 2013;788:174-177.
18. Madhukumar R, Nayaka R, Mathad G, Subramanya K, Pathar D, Gurikar SG, *et al*. Influence of Ionizing Radiation on Bio-synthesis of Noble Metal SF-AgNPs: Their Applications. Indian Journal of Science and Technology. 2025;18(22):1792-1800.
19. Marelli B, Brenckle MA, Kaplan DL, Omenetto FG. Silk fibroin as edible coating for perishable food preservation. Scientific Reports. 2016;6(1):25263.
20. Mondal M, Trivedy K, Kumar SN. Extraction of Liquid and Powder Fibroin from Cocoon Shell of Silkworm (*Bombyx mori* L.). Journal of the Entomological Research Society. 2007;9(3).

21. Myung SJ, Kim HS, Kim Y, Chen P, Jin HJ. Fluorescent silk fibroin nanoparticles prepared using a reverse microemulsion. Macromolecular Research. 2008;16:604-608.
22. Panayotov M, Gancheva R. Fibroin content in raw silk from *Bombyx mori* L. cocoons with different fluorescent characteristics nanoparticles as carriers. Nanotechnology. 2015;24:035103.
23. Pandey R, Khuller GK. Nanotechnology based drug delivery system(s) for the management of tuberculosis. Indian Journal of Experimental Biology. 2006;44(5):357-366.
24. Pereira RFP, Silva MM, de Zea Bermudez V. *Bombyx mori* Silk Fibers: An Outstanding Family of Materials. Macromolecular Materials and Engineering. 2015;300:1171-1198.
25. Pham DT, Tiyaboonchai W. Fibroin nanoparticles: a promising drug delivery system. Drug Delivery. 2020;27(1):431-448.
26. Rockwood DN, Preda RC, Yucel T, Wang X, Lovett ML, Kaplan DL. Materials fabrication from *Bombyx mori* silk fibroin. Nature Protocols. 2011;6:1612-1631.
27. Rodrigues CL, Tomoda BT, Viganó J, Braga ARC, de Moraes MA, Veggi PC. Production and Characterization of Silk Fibroin-Aloe vera Hydrogel: A Study on Extraction, Hydrogel Properties, and Release Mechanism. ACS Omega. 2024;9(51):50515-50525.
28. Sah MK, Pramanik K. Regenerated silk fibroin from *B. mori* silk cocoon for tissue engineering applications. International Journal of Environmental Science and Development. 2010;1(5):404.
29. Sah MK, Kumar A, Pramanik P. The extraction of fibroin protein from *Bombyx mori* silk cocoon: Optimization of process parameters. International Journal of Bioinformatics Research and Application. 2010;2:33-41.
30. Saraswathy N, Balaji S, Veerichetty V, Ponnusamy R, Muthukumaran P, Sankavi T, *et al*. In Situ Synthesis of Silk Fibroin Mediated Silver Nanoparticles in Chitosan-Peo Film and Studies on Release Kinetics for Wound Dressing Application. Journal of Chemical and Pharmaceutical Sciences. 2018:2349-8552.
31. Sasaki T, Noda H. Studies on silk fibroin of *Bombyx mori* directly extracted from the silk gland: I. Molecular weight determination in guanidine hydrochloride or urea solutions. Biochimica et Biophysica Acta (BBA)-Protein Structure. 1973;310(1):76-90.
32. Sashina ES, Bochek AM, Novoselov NP, Kirichenko DA. Structure and solubility of natural silk fibroin. Russian Journal of Applied Chemistry. 2006;79:869-876.
33. Sharma M, Bordoloi S, Mazid S, Baruah SG. Silk fibroin extraction and quantification of silk powder from cocoons of *Philosamia ricini* (Eri) *Antheraea assamensis* (muga). Journal of Emerging Technologies and Innovation Research. 2018;5:234-252.
34. Sheng W, Liu J, Liu S, Lu Q, Kaplan DL, Zhu H. One-step synthesis of biocompatible magnetite/silk fibroin core-shell nanoparticles. Journal of Materials Chemistry B. 2014;2(42):7394-7402.
35. Shivananda CS. Silk fibroin-based green colloidal silver nanoparticle synthesis and their antibacterial and anticancer properties. Inorganic Chemistry Communications. 2023;158:111611.
36. Su X, Wei L, Xu Z, Qin L, Yang J, Zou Y, *et al*. Evaluation and application of silk fibroin based biomaterials to promote cartilage regeneration in osteoarthritis therapy. Biomedicines. 2023;11(8):2244.
37. Tsukada M, Freddi G, Minoura N, Allara G. Preparation and application of porous silk fibroin materials. Journal of Applied Polymer Science. 1994;54(4):507-514.
38. Vidya M, Senthilkumar R. Silk Fibroin: A Promising Tool for Wound Healing and Skin Regeneration. International Journal of Polymer Science. 2021;98:101-112.
39. Wray LS, Hu X, Gallego J, Georgakoudi I, Omenetto FG, Schmidt D, *et al*. Effect of processing on silk-based biomaterials: Reproducibility and biocompatibility. Journal of Biomedical Materials Research. 2011;99:89-101.
40. Zhang G, Liu Y, Gao X, Chen Y. Synthesis of silver nanoparticles and antibacterial property of silk fabrics treated by silver nanoparticles. Nanoscale Research Letters. 2014;9(1):216.
41. Zhang YQ, Shen WD, Xiang RL, Zhuge LJ, Gao WJ, Wang WB. Formation of silk fibroin nanoparticles in water-miscible organic solvent and their characterization. Journal of Nanoparticle Research. 2007;9:885-900.
42. Zhao Z, Li Y, Chen AZ, Zheng ZJ, Hu JY, Li JS, *et al*. Generation of silk fibroin nanoparticles via solution-enhanced dispersion by supercritical CO2. Industrial & Engineering Chemistry Research. 2013;52(10):3752-3761.
43. Zheng Z, Guo S, Liu Y, Wu J, Li G, Liu M, *et al*. Lithium-free processing of silk fibroin. Journal of Biomaterials Applications. 2016;31(3):450-463.
44. Zheng Z, Yili, Ma BX. Silk Fibroin-Based Nanoparticles for Drug Delivery. International Journal of Molecular Science. 2015;16(3):4880-4903.
45. Zhou CZ, Confalonieri F, Jacquet M, Perasso R, Li ZG, Janin J. Silk fibroin: structural implications of a remarkable amino acid sequence. Proteins: Structure, Function, and Bioinformatics. 2001;44(2):119-122.