



Review Article

Silk Nano Fibroin Preparation, Characterisation and Biomedical Applications – A Review

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ABSTRACT

Silk Fibroin (SF), a natural biopolymer obtained from *Bombyx mori* cocoons, has gained increasing attention in the area of science and technology due to its biocompatibility, mechanical, and tunable properties, and degradability. SF is a versatile platform for next-generation biomedical technologies. Nano-SF (NF), produced through bottom-up and top-down strategies, extends the technological utility by enabling enhanced cell-material interactions, controlled therapeutic delivery, and the formation of extracellular matrix-mimetic nanoarchitectures. This review explains SF-sericin separation methods by degumming processes with emerging methods designed to improve yield, reproducibility, and structural preservation of SF. Subsequent SF extraction workflows are discussed, followed by a detailed overview of NF fabrication techniques, including electrospinning, mechanical milling, microfluidic synthesis, and self-assembly. Characterisation tools and techniques for understanding NF, such as Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD), and related analytical techniques. The integration of NF into polymeric, ceramic, and bioactive composite systems has enabled the development of multifunctional scaffolds with tailored mechanical, biological, and degradation profiles. These NF-based technologies demonstrate broad applicability in wound healing, tissue engineering, neural regeneration, and localised drug delivery, and emerging commercial devices incorporating SF and NF, highlighting opportunities and barriers for successful clinical and industrial adoption.

Keywords: Biomaterial, Biomedical, Composites, Nano fibroin, Silk, Silk fibroin

1. INTRODUCTION

Silk has a rich history and is one of the oldest known materials, used for over 5,000 years in various applications. Silk is of various types, classified based on the species of silkworm spun at different geographical locations, depending on their habitats, as shown in Table 1, with its primary application in textiles. With selective breeding, the Bombyx. The Mori (*B.mori*) strain is domesticated for the production of silk, improving the quality, yield, and mechanical strength of silk for various other applications.^[1] Silk Cocoon is the outer shell spun by the silkworm as a protective shell composed of two main proteins, silk fibroin (SF) and silk sericin (SS). SF is the structural core protein with a parallel fibre coated with SS, a glue-like protein, as illustrated in Figure 1, and can be separated by a process of degumming.^[2] Concentration of SS and SF in the silk cocoon varies generally in the ratio of 70–80% of SF and SS 20–30% of the total weight of the cocoon^[3] SF is composed of 45.9% glycine (G), 30.3% alanine (A), 12.1% serine (S), 5.3% tyrosine, 1.8% valine, and 4.7% other amino acids composition with major repeats as GAGAGS^[4] sericin composed of 30.4% Serine, 19.4% Aspartic acid, 12.2% Glycine and other amino acids.^[5] The

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Table 1: Types of silk, Species and Geographical Location

| Silk type | Silkworm species | Geographical location |
|----------------|---|--|
| Mulberry | <i>B.mori</i> | India, China, Brazil, France, Italy, Japan, Korea, Russia |
| Tasar (Tussar) | <i>Antheraea mylitta</i> | India (Jharkhand, Chhattisgarh, Odisha, Maharashtra, West Bengal, Andhra Pradesh) |
| Oak Tasar | <i>Antheraea proylei</i> (India) <i>Antheraea pernyi</i> (China) | India (Manipur, Himachal Pradesh, Uttar Pradesh, Assam, Meghalaya, Jammu & Kashmir), China |
| Eri | <i>Philosamia ricini</i> | India (Assam, West Bengal, Bihar, Odisha, Meghalaya, Nagaland, Manipur) |
| Muga | <i>Antheraea assamensis</i> | India (Assam) |
| Anaphe Silk | <i>Anaphe</i> | Central and Southern Africa |
| Fagara Silk | <i>Attacus atlas</i> | Indo-Australian region, China, Sudan |
| Spider Silk | Various spider species | Produced in limited quantities worldwide |
| Coan Silk | <i>Pachypasa otus</i> | Mediterranean region (Italy, Greece, Turkey, Romania) |

**Figure 1:** Silk and silk proteins.

strong hydrophilic nature of sericin is characterised by 45.8% polar hydroxyl amino acids.^[6]

SF consists of a heavy chain (~390–391kDa) and a light chain (~26 kDa), forming a high molecular weight (~420 kDa) complex. Structurally, it features repetitive GAGAGS motifs forming β -sheet crystalline domains (Silk II). Crystallinity arises from nanoscale β -sheet crystallites. Its strength, biocompatibility, and shear-thinning behaviour make it ideal for biomedical applications.^[7] Silk threads is used for centuries as a suture material, initially documented by Galen in 150 AD and reintroduced in sterile form by Joseph Lister in 1869,^[8] SF biocompatibility and ability to promote cellular attachment and growth have made it a material of choice

in wound healing and tissue regeneration,^[9] SF can serve as a matrix for controlled and sustained drug release due to its ability to encapsulate bioactive molecules and provide a controlled degradation rate.^[10]

Nanotechnology and its application in Biomaterial science enhance material properties for its advanced applications^[11] and have enhanced properties such as cellular attachment, adherence, proliferation, and migration, and also differentiation and survival of defined cell types.^[12] Hence, material processed to nano-sized ranging from 1 to 1000 nanometres with desired properties can have advanced applications. Nano-SF (NF) refers to SF that has been processed into nanoscale structures such as nanoparticles, nanofibres, and nanocomposites, offering distinct advantages over traditional SF, which exhibits a higher surface area-to-volume ratio compared to bulk SF, due to interactions with cells, proteins, and other biomolecules. This is particularly advantageous in applications such as drug delivery, where increased surface area enhances drug loading capacity and interaction with target sites.^[13] Nano-sized SF's ability to encapsulate hydrophobic and hydrophilic drugs is highly effective; the nanofibrous structure helps in sustained or targeted release, reducing the frequency of administration and improving therapeutic outcomes.^[14] NF has been widely used in tissue engineering, particularly in the regeneration of skin, bone, cartilage, and neural tissues. The fibrous structure mimics the extracellular matrix (ECM), promoting cell attachment, proliferation, and differentiation, and its degradability allows for gradual replacement by natural tissue as regeneration occurs. The nanoscale structure enhances the mechanical properties, such as elasticity and strength, making it ideal for applications where scaffolds support growing tissues.^[15] NF has intrinsic antibacterial properties further enhanced by incorporating antimicrobial agents like silver nanoparticles, copper, and other bioactive molecules. This

makes nano-SF-based materials ideal for preventing infection in wound dressings and tissue engineering scaffolds.^[10]

2. METHODS OF SF EXTRACTION

Extraction of SF starts with the separation process of SS and SF from the silk cocoon by degumming. Sericin is soluble in water, and fibroin is not soluble in water. The degumming process can be carried out with the aid of alkali, acids, enzymes, urea, ultrasonic waves, microwaves, etc.^[16] The most widely used method among researchers and industries is alkali degumming.^[17] Alkaline degumming involves process of boiling cocoons in presence of Sodium carbonate as widely used alkali for degumming at different time points and the process also mentioned as boiling, autoclaving, long time degumming, short time degumming at different temperatures and each process impact the properties with both advantages and disadvantages for its end use^[18] on completion of degumming the fibres are washed, rinsed with water several times to remove residual sericin, impurities and dried.^[19] SF is not soluble in water and most organic solvents, but swells to 30 – 40% as amorphous regions hold water. Its insolubility is due to a large amount of intra- and intermolecular hydrogen bonding and high crystallinity, unlike other glycoproteins.^[20] To solubilise SF or to produce Regenerated SF (RSF) systems containing concentrated salts or acids that disrupt intermolecular interactions is suitable. Solvents such as lithium bromide, calcium chloride in ethanol-water mixtures, and certain ionic liquids are particularly effective in breaking the hydrogen bonds and hydrophobic interactions within the SF structure. The solubility also depends on factors like temperature, pH, and the degree of SF's molecular degradation, which can alter its chain length and conformation. Regenerated SF, which has a more disordered structure, dissolves more readily in solvents like N-methyl morpholine N-oxide compared to native SF^[21] most widely used methods of dissolution is by lithium bromide(LiBr) using 9.3M lithium bromide were degummed fibres are dissolve in 9.3M lithium bromide at 70 – 90°C for 3 to 4 hours followed by desalting using dialysis bags, filtration membranes etc. The other method is by Calcium chloride (CaCl₂) method, also known as the Ajisawa method, the ternary solvent method. This method uses calcium chloride, water, and ethanol in the molar ratio 1:8:2, dissolution will be carried out with varied time points at different temperatures, followed by with and without reflux systems based on temperatures, followed by desalting and filtration.^[22]

3. METHODS OF NANO SF PREPARATION

3.1 Electrospinning

SF dissolved in formic acid (10% w/v) to prepare the spinning solution. Electrospinning was performed using a

15 kV voltage, 0.3 mL/h flow rate, and 15 cm tip-to-collector distance. Nanofibres were collected on an aluminium foil-wrapped collector and treated with 90% methanol to induce β -sheet crystallinity. Resulting in 30–120 nm diameter fibre size.^[23] SF dissolved in formic acid–calcium chloride solution (10% w/v). Needleless electrospinning was performed using a rotating roller at 30 kV and 10 cm distance, producing uniform nanofibres with morphology and diameter (100–2400 nm) were characterised using SEM. FTIR analysis confirmed β -sheet structure, and XRD validated crystallinity.^[24]

3.2 Electro-spraying

The SF sponge prepared by Ajisawa dissolution, subjected to lyophilisation, and then dissolved in 98% formic acid and electro-sprayed using a high-voltage setup, where a fine jet of liquid is broken into nanoparticles under an electric field. Key parameters such as solution concentration, voltage 10–30 kV, feed rate 0.053–0.132 ml/h, and needle-to-collector distance 10–15 cm.^[25] A 2.0% (w/v) SF solution was electrostatically differentiated into droplets, collected, and lyophilised, which resulted in SF nanoparticles of size approximately 59 nm.^[26]

3.3 Mechanical milling

In mechanical milling, a suitable powder charge is placed in a high-energy mill, along with a suitable milling medium, with the objective of milling to reduce the particle size. The different types of ball milling can be used for the synthesis of nanomaterials. Balls roll down the surface of the chamber in a series of parallel layers, or they fall freely and impact the powder and balls beneath them. The kinetics of mechanical milling or alloying depends on the energy transferred. multivoltine mulberry cocoons, wild muga cocoons were cut and cleaned followed by series of degumming with A cutter mill with five “V” shaped blades fitted on a rotor used for chopping degummed cocoons which rotates at 2888 rpm in combination with three fixed blades cut the fibres until they become fine enough to pass through a 1 mm grid followed by Rotary milling fitted with a 0.08 mm sieve operated with a speed of 20,000 rpm. milled material was driven out by rotor-generated air flow and subsequently collected using a cyclone by milling repeatedly for up to 15 times [Figure 2].^[27] An air jet mill with a grinding air pressure of 110 kg/cm² was used involving process of feeding by a powder hopper at a feed rate of 200 g/h followed by spray drying to obtain dry powders from wet milled slurry were recovered through a laboratory spray dryer^[28] wet ball milling using Cerium-doped zirconium oxide grinding media of 0.5–0.6 mm having a volume of 55–60 ml was used with milling speed adjusted between 1500 to 4000 rpm by maintaining temperature 18°C by Cooling water circulation run through the jacket of the milling chamber to prevent thermal degradation while milling, 100 mL of pH 3 solution prepared

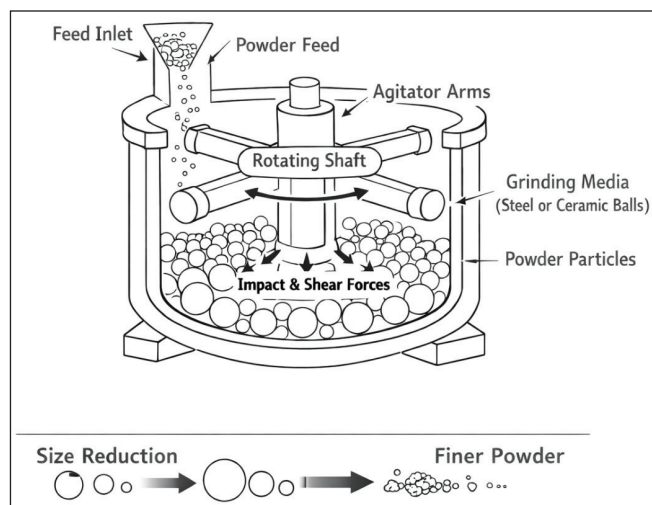


Figure 2: Attrition ball milling.

by a combination of 25 mL potassium hydrogen phthalate 0.2 M and 11.15 mL hydrochloric acid 0.2 M and pH 10 was achieved by a combination of 25 mL sodium bicarbonate 0.1 M and 5.35 mL sodium hydroxide 0.2 M followed spray drying and lyophilisation to obtain nano particles.^[29]

3.4 Ultrasonic mediated

Lyophilised RSF prepared by Ajisawa method was dissolved in formic acid in combination with soy protein isolate with calcium chloride in different concentrations the blend was then treated with an ultrasound device probe equipped with 2 mm diameter titanium microtip with ultrasonic power 800 W, and the end of the ultrasonic probe was placed 10 mm below the surface of the solution for different time points after ultrasonic treatment, samples spray spinned using spray spinning equipment which resulted in particle size of 130-200 nm, SF is dissolved using ionic liquids by the aid of ultra-sonication followed by coagulation, washing to obtain regenerated silk nano particles of range 200nm size.^[30]

3.5 Desolvation

The desolvation technique is a method for preparing nanoparticles from proteins like silk SF. It relies on the reduction of a protein's solubility by adding a desolvating agent, typically an organic solvent, to induce aggregation and particle formation.^[31] RSF prepared by lithium bromide dissolution method and the desolvation process is carried out by using desolvating agent dimethyl sulphoxide, the process involved 10 ml of 2% RSF drop wise added to desolvating agent under continuous stirring followed by centrifugation and washing resulting the particle size <200 nm,^[32] RSF introduced in acetone to with continuous stirring and generated nano particles of size <300 nm.^[33]

3.6 Salting out

This technique is based on the parting of a water-miscible solvent from aqueous solution by adding a salting-out agent such as magnesium chloride, calcium chloride, etc. The main advantage of a salting out procedure is that it minimises the unfolding stress to protein encapsulates Salting out removes proteins that easily aggregate from those that are very soluble, making it a good initial purification step for small soluble proteins.^[34] RSF prepared by LiBr dissolution method dialysed by 30Kda cassette and centrifuged to remove any aggregates as well as debris from the original cocoons. SF particles were prepared by phase separation from an aqueous protein solution by the addition of potassium phosphate for particle formation and stored in a refrigerator for 2 h, and centrifuged at 2000g for 15 min. The particles were re-dispersed in purified water and washed three times. The ionic strength, pH, and protein concentration were studied systematically.^[35] SF particles were produced by salting out with potassium phosphate. The process involved mixing an aqueous SF solution with potassium phosphate at a specific molarity (typically 1.25 M) and pH, leading to phase separation and particle formation.^[36]

3.7 Solution enhanced dispersion (SEDS)

The SEDS apparatus consists of high-pressure vessels and pumps designed to handle supercritical CO₂ and the SF solution by injecting the SF solution into the high-pressure vessel containing supercritical CO₂ through a nozzle. Upon contact, the supercritical CO₂ rapidly reduces the solvent's solubility, leading to the precipitation of SF nanoparticles, which are collected after depressurisation and removal of CO₂. The SEDS process produced SF nanoparticles with sizes ranging from 52.5 to 102.3 nm.^[37]

3.8 Microfluidic- assisted

Microfluidic devices designed for precise fluid manipulation at the micro-scale offer a unique platform for attaining NP properties, enabling control over NP properties such as morphology, size, Shape and distribution while ensuring high reproducibility. Its unique precision in tailoring NP properties holds great promise for advancing NP-based drug delivery systems in both clinical and industrial settings,^[38] RSF prepared by LiBr dissolution method Silk nanoparticles were produced using a Nano- Assembler benchtop instrument version 1.5 equipped with a micro fluidic cartridge with 3% w/v aqueous silk solution and organic solvent either acetone or isopropanol injected into separate chamber inlets, the silk nano precipitated in the micro fluidic mixer resulting nanoparticles.^[39]

4. CHARACTERISATION TECHNIQUES

4.1 Structural characterisation

4.1.1 Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared (FTIR) spectroscopy probes the vibrational properties of amino acids and cofactors, which are sensitive to minute structural changes. The lack of specificity of this technique, on the one hand, permits us to probe directly the vibrational properties of almost all the cofactors, amino acid side chains, and water molecules.^[40] FTIR is one of the main tools for the study of the composition of silk materials. Studies on SF used direct curve fitting of the broad amide I region, fitted in the spectrum introduced for the accurate quantitative study of the beta-sheet fraction in SF.^[41] Characteristic vibration peaks at 1650–1630 cm^{-1} , 1540–1520 cm^{-1} , and 1270–1230 cm^{-1} for amide I, amide II, and amide III, respectively, for SF nanoparticles [Figure 3].^[42]

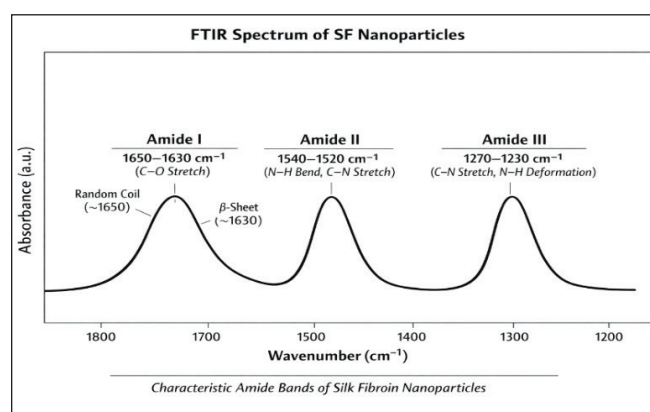


Figure 3: Amide bonds indication. FTIR: Fourier transform infrared spectroscopy, SF: Silk fibroin

4.1.2 X-ray diffraction (XRD)

X-ray powder diffractometers (XRPD) are an important technique to determine the crystalline phase of the samples. SF has crystalline and amorphous states in different conditions, and the crystalline state includes silk I (α -helix) and silk II (β -sheet) indicating On the XRD curves, the main diffraction peaks of silk I were 12.2°, 19.7°, 24.7°, 28.2°, etc., and peaks of silk II were 9.1°, 18.9°, 20.7°, etc.^[36,43]

4.2 Morphological characterisation

4.2.1 Scanning electron microscopy (SEM)

Scanning Electron Microscopy (SEM) is a powerful imaging technique used to study the surface morphology and composition of materials at high magnification. It uses a focused beam of high-energy electrons to interact with

the sample surface, producing signals that reveal detailed information about the sample's topography. SEM images were used to evaluate the effectiveness of milling and drying methods by observing surface smoothness, particle size, and aggregation levels.^[44]

4.2.2 Particle size analysis

Dynamic Light Scattering (DLS) is a technique used to measure the size distribution of small particles and molecules in suspension.^[45] It works by analysing the fluctuations in the intensity of scattered light caused by particles undergoing Brownian motion. DLS confirmed the ability of optimised bead milling to produce submicron silk particles. DLS highlighted the differences in particle size distribution caused by different surfactants, pH levels, and drying methods. The narrow size distribution observed with Tween 80 confirmed its effectiveness in achieving uniform particles.^[46]

4.3 Chemical and compositional analysis

4.3.1 Nuclear magnetic resonance (NMR)

NMR spectroscopy with vivid experiments in the form of liquid state and solid state, one-dimensional, two-dimensional, and multidimensional, can provide a deep insight into molecular weight, purity, composition, structure, dynamics, diffusion properties, stoichiometry of nano materials,^[47] NMR studies indicate the ^{13}C chemical shifts of the alanine's indicating the presence of helices and random coils, and solid state studies of the lyophilised protein show evidence of both 310-helices and a-helices, folding into the b-sheet conformation.^[48]

4.4 Thermal characterisation

4.4.1 Differential scanning calorimetry (DSC)

DSC is a thermoanalytical technique used to measure the heat flow associated with phase transitions in materials as a function of temperature or time. It identifies thermal events such as melting, crystallisation, glass transitions, and thermal decomposition. The influence of composition and heat treatment on the thermal properties aids in optimising these materials.^[49] The study analysed silk sericin and SF nanofibres and blends using DSC to explore their thermal properties. DSC revealed critical thermal properties of silk-based nanofibres, including their thermal stability and decomposition behaviour.^[50]

4.5 Biochemical and functional characterisation

4.5.1 Circular dichroism (CD) spectroscopy

CD is a technique used to analyse the secondary structures of chiral molecules, proteins, and nucleic acids. It measures

the difference in the absorption of left- and right-circularly polarised light, which arises due to the chiral nature of the sample.^[51] CD spectra were recorded for the native SF, and after its incubation under fibrillation conditions for 30, 60, and 120 minutes. In the spectra, upon increment in the fibrillation time, the ellipticity values at 197 nm increased. This indicated that in comparison with the native protein, incubation under fibrillation conditions leads to increasing the random coil conformations in the protein structure and eliminates the structural characteristic of the protein.^[52] CD spectra of the original SF solutions with different concentrations showed a negative ellipticity at about 195 nm, indicating random conformation formation.^[53]

5. NANO SF-BASED FORMULATIONS

SF-based nano formulations are derived from SF by utilising different processing techniques such as electrospinning, nanoprecipitation, solvent evaporation, and self-assembly. These formulations can take a variety of shapes, including nanoparticles, nanofibres, and films. By incorporating active compounds such as drugs, proteins, or growth factors, SF nano formulations hold great promise for numerous biomedical applications, including drug delivery, wound healing, tissue engineering, and cancer therapy.

5.1 Nanosphere

The formulation process of nanospheres by SF and PVA involved dissolving the SF and PVA in a solvent, followed by casting the blend into films and using a solvent evaporation method to create nanospheres. This blend enhanced the encapsulation efficiency for various drugs, including proteins and small molecules, and provided controlled release profiles.^[54] SF combined with gelatine to create a composite system that could deliver biomolecules in a sustained and controlled manner. The gelatine nanospheres, encapsulating the biomolecules, were integrated into electrospun SF nanofibres, which serve as a supportive scaffold.^[55]

5.2 Nano capsule

Silk-like protein from the mollusc *Mytilus edulis*, with *B. mori* SF to create fusion proteins capable of self-assembling into nano capsules. The nanoprecipitation technique was employed to generate these nano capsules, where the fusion proteins were dissolved in an organic solvent and then rapidly precipitated into nanoparticles by adding them to a non-solvent. This method produced nano capsules with controlled size and excellent encapsulation efficiency for various bioactive compounds, including hydrophobic drugs.^[56]

5.3 Nano fibres

Curcumin-loaded electro spun nanofibrous mats were prepared by blending polycaprolactone (PCL), polyvinyl alcohol (PVA), and silk SF. The mats were characterised for their morphology, mechanical strength, and drug release properties, and in vitro and in vivo studies demonstrated their potential for promoting wound healing in diabetic wounds.^[57]

5.4 Nano SF-based scaffolds

Preparation of layered chitosan/silk SF/nano-hydroxyapatite scaffolds involved a systematic, layer-by-layer fabrication process to achieve desired mechanical and biological properties for bone tissue engineering, resembling the hierarchical structure of natural bone tissue and demonstrating promising performance in vitro.^[58] Nonwoven SF, where the SF solution was subjected to a high-voltage electric field to form nanofibres, which were collected on a grounded collector. The prepared net was then impregnated with nHA particles to form the composite scaffold. The scaffold was freeze-dried and crosslinked to improve mechanical integrity. In vitro tests confirmed that the scaffold supported osteoblast adhesion and proliferation, highlighting its potential for bone regeneration applications.^[59]

6. APPLICATIONS OF NANO FIBROIN

6.1 Wound healing

NF compared to the SF control, the NF exhibited a nanopore surface morphology as well as higher ductility and permeability of oxygen and nutrition, promoting cell proliferation. An in vivo study demonstrated that the NF showed superior performance in vascularisation and collagen deposition and achieved a significant improvement in the quality of wound healing, promoting tissue regeneration.^[60] SF nano particles (NPs) were used to produce a hydrocolloid dressing; the results showed water uptake and swelling ratios, indicating that SF NPs increased the elasticity due to their viscosity. Further, results showed that cell growth rate increased with the content of the SF NPs through the CCK-8 assay.^[61] Enhanced wound healing incorporates nanoparticles (NPs) loaded with neomycin (NM) antibiotic and an organic extract. Results demonstrated that the tested compounds are cytotoxicity with no cytotoxicity and of relatively high antioxidant potential, as well as a marked antibacterial activity.^[62]

6.2 Drug delivery

Metronidazole (MNZ)/poly lactic-co-glycolic acid (PLGA)/SF (SF) nanofibres, a membrane prepared by electro spraying technique, were physically embedded together, and

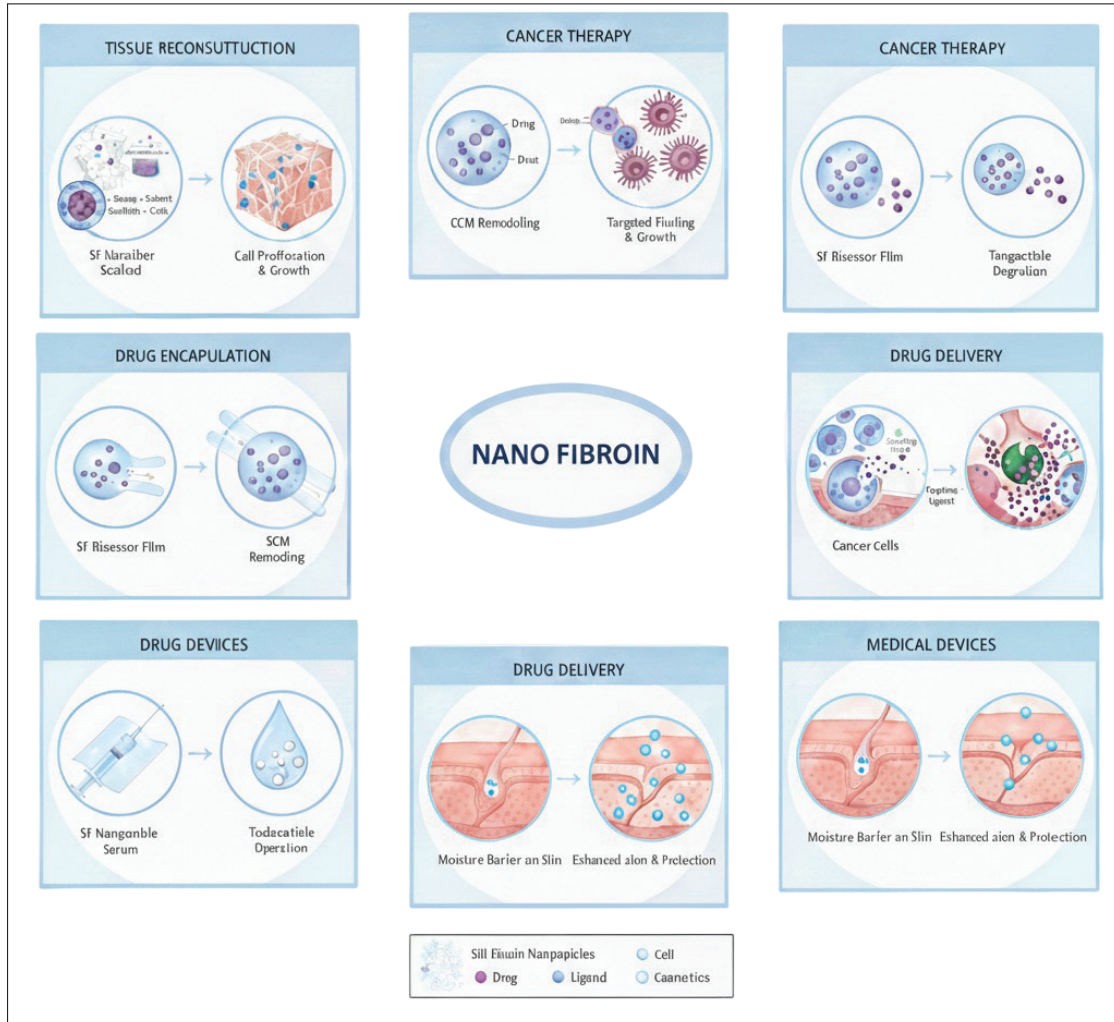


Figure 4: Applications of nano fibroin. SF: Silk fibroin, CCM: Chromatin remodeling complexes, SCM: Scanning electron microscopy.

each group of molecules exhibited good physicochemical properties. With the addition of MNZ, PLGA gradually changed from a hydrophobic to a hydrophilic membrane, and the hydrophilicity was enhanced with the gradual increase of SF. MNZ/PLGA/SF nanofibres demonstrated good biocompatibility and thermal stability. The results indicated that the 3wt% MNZ/PLGA/SF 2:1 nanofibres had a better water absorption rate, in vitro degradation rate, and drug release.

Genetically modified SF nanoparticles are promising in targeted drug delivery due to their biocompatibility, mechanical strength, and tunable biodegradability. Applications include tumour-targeted therapy via ligand-modified NPs, cytoplasmic drug delivery using cell-penetrating peptides, and improved drug release through enhanced β -sheet structures. GMSF -NPs can also be engineered for enzyme- or temperature-responsive drug release, and fluorescent tagging for tracing drugs.

Incorporating bioactive peptides further enhances drug efficacy and stability. These versatile applications enable precise, effective treatments with reduced side effects, especially in cancer and inflammatory disease therapies. Future research may expand their roles in precision medicine and personalised therapeutics [Figure 4].^[62]

6.3 Cancer therapy

The physical-chemical properties of SF NSF were prepared by the desolvation technique; all formulations were cytocompatible, with curcumin encapsulation reducing its cytotoxicity, and iron oxide not affecting cell metabolic activity and easily taken by cells. SF Ns-Fe were useful for preliminary bio-distribution studies, as MRI confirmed significant retention at the administration site with only a slight to moderate iron accumulation in lymphoid tissues, lymph nodes, and spleen, revealed by histological analysis, supporting their potential for localised cancer therapy.^[63]

Curcumin-loaded SF Ns [Curc-SF Ns] were synthesised, with curcumin encapsulated on the SF Ns but not in its free state. The antioxidant activity against DPPH showed that the curcumin loaded in Curc-SF Ns retains full antioxidant activity. The Curc-SF Ns enhanced the antitumor activity of curcumin towards the two different tumour cell lines studied, resulting in no decrease in normal cells.^[50]

6.4 Tissue reconstruction

SF-based scaffolds can be used for constructing artificial corneal matrices, as they offer optical transparency, which is crucial for vision restoration. These scaffolds support cell adhesion, migration, and proliferation, making them suitable for promoting the regeneration of corneal epithelial and stromal cells by integration with other materials, such as nano-hydroxyapatite makes it a versatile candidate for complex tissue regeneration in ocular repair.^[64] SF foams embedded with gold, silver, and iron oxide nanoparticles exhibited homogeneous porosity, good mechanical strength, and shape recovery properties. In vitro and in vivo tests confirmed high biocompatibility, low cytotoxicity, and minimal inflammation. Implanted foams supported cellular adhesion, vascularisation, and extracellular matrix synthesis, indicating successful tissue integration.^[65]

6.5 Cosmetics

Silk proteins are widely utilised in skincare and haircare products due to their beneficial properties, including moisturising, smoothing, and skin-repairing effects, safety assessment in the study concluded that silk protein ingredients, when used within established concentrations, do not pose significant health risks, confirming their safety for use in cosmetic formulations. This makes SF an attractive ingredient in the cosmetic industry for its skin conditioning, anti-ageing, and protective benefits.^[66] SF nanofibrous mats were fabricated to serve as a controlled delivery system for vitamin E, a potent antioxidant known for its skin-protective and anti-ageing properties. The SF mats were created using electrospinning, which enabled the formation of nanofibres with a high surface area and porosity, ideal for loading and releasing vitamin E. benefits.^[67]

6.6 Wound healing

Wound healing has seen significant advancements with the development of innovative biomaterials and medical devices. These advancements include the use of bioactive materials such as hydrogels, nanofibres, and scaffolds that promote tissue regeneration and reduce infection risks. Smart wound dressings embedded with sensors can monitor healing in real-

time, providing critical data on factors like moisture levels, pH, and infection indicators. Integration of biocompatible materials, such as collagen, chitosan, and synthetic polymers, has improved the efficacy of wound care treatments. Such innovations have applications in treating chronic wounds, such as diabetic ulcers and pressure sores, as well as in post-surgical recovery, enhancing patient outcomes and reducing healthcare costs.^[68]

7. PRODUCTS BASED ON SILK SF

Silk-based biomaterials have emerged as promising candidates in biomedicine and biotechnology due to their exceptional biocompatibility, biodegradability, and mechanical versatility. SF is a key protein derived from silk and processed into various forms, such as films, fibres, hydrogels, and scaffolds, enabling diverse applications in tissue engineering, drug delivery, wound healing, and bioelectronics, highlighting recent advancements in silk-based biomaterials and their applications in regenerative medicine and biotechnology, and major biotech companies commercialised silk are Fibroheal Woundcare Pvt. Ltd., AM Silk, Silk tears, Sylke etc.,^[69]

8. CONCLUSION

NF production techniques, such as electrospinning, milling, ultrasound treatment, and microfluidics, which allow precise control over particle size and structure. These nano-forms can be combined with other materials to form composites that enhance biological activity and structural support. NF is especially useful in wound healing, targeted drug delivery, tissue engineering, and even cancer therapy, as it mimics natural tissue environments and supports cell growth, while enabling controlled release of therapeutic agents. It is also finding use in cosmetic products for skin repair and moisturising. Real-world medical products, such as wound dressings and bioactive films, are already incorporating NF-based formulations. With its versatility and safety, NF is set to play a vital role in the future of biomedicine, personalised therapeutics, and sustainable material development, bridging traditional natural materials with cutting-edge science.

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Declaration of patient consent: Patient's consent not required as there are no patients in this study.

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