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Bio-Nanotechnological Advances in Sericulture: Applicability of Micrococoons and Silk Proteins

Sangeeta Dash*, Mohd Anas, Reddi Gowrisankar and Surekha Dasari
Ph.D. Research Scholar, Division of Entomology,
ICAR-Indian Agricultural Research Institute New Delhi, India.

(Corresponding author: Sangeeta Dash)*
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ABSTRACT: Biotechnology and Nanotechnology are considered as weapons that can devise constructive solutions to address global issues. The unit production cost of Indian silk is higher as compared to China. Thus, the need of the hour is to devise innovative applications of silk and silk proteins, value addition, byproduct utilisation and diversification thus minimalizing the wastes generated. This will curtail the production costs and make Indian silk cheaper for the consumers to buy in domestic and overseas markets. The unique application of biotechnology in sericulture encompasses the use of transgenic silkworms to generate fine-quality cocoons, bioengineering silk as a bioactive material owing to its strength, biocompatibility, elasticity, robustness, biodegradability, etc. Thus, silk proteins turn out to be an effective biomaterial with multifarious applications in the food and pharmaceutical industries. Micrococoons, inspired by silkworm cocoons can serve as a potent vector for the delivery of useful drugs, proteins, vaccines, genes, and micromolecules. This finds application in the treatment of osteomyelitis and dermal disorders. Owing to its excellent mechanical properties, biocompatibility and low immunogenicity, silk sericin and fibroin have multiple bio-medical applications in cartilage and bone regeneration and tissue engineering. Nanotechnology in sericulture helps to build structures that are crucial for water purification, drug delivery, devising sensors, and optics and photonics. Therefore, the present review highlights the recent advances in comprehensive utilization and diversification of biotechnological and nanotechnological knowledge to devise products of commercial use broadening the sustainability of the sericulture industry.

Keywords: Biotechnology, Bioengineering, Micrococoons, Nanotechnology, Sericulture.

INTRODUCTION

Sericulture, the art of rearing silkworms to produce natural silk fibers (Gautam *et al.,* 2022), is an agro-based cottage industry practiced commercially in nearly 25 countries employing 30 million people globally (Sharma *et al.,* 2022). It is a labour-intensive rural industry that yields numerous by-products and co-products apart from lustrous silk. Silk Cocoon is an exemplary citation of marvellous bioengineering skills of tiny worms that inspires human architecture. Silk owing to its strength, elegance, elasticity, flexibility, versatility, and mechanical and tensile properties, is reputed as "Bio steel (Anonymous, 2021)." The chemical composition of silk includes carbohydrates, proteins (sericin and fibroin), waxes, inorganic matter, and pigments (Silva *et al.,* 2022). Thus, silk is a natural biodegradable, and biocompatible polymer that refines its bio-medical profitability (Lamboni *et al.*, 2015). Silk protein, sericin finds numerous cosmetological applications due to its anti-oxidant, anti-microbial, moisturising, and healing actions along with pharmaceutical importance as UV-screening properties and anti-tumor action (Buhroo *et al.,* 2018). Additionally, the mulberry silkworm *Bombyx mori* L. serves as a model organism for basic biological research, physiological studies, ecological monitoring, and bioreactor to produce recombinant proteins and vaccines (Meng *et al.*, 2017). The various nano-scale structures obtained from silk are hydrogels, films, silk solutions, fibers, scaffolds, mats, sponges, coatings, aerogels, and 3Dmatrices (Belda Marin *et al.*, 2020). This approves their use as bio-materials and biomedicines, water filtration systems, electronic devices, and environmentally adaptive materials. Utility of silkworms as bioreactors to express foreign proteins (nearly 10 proteins) as human and animal proteins, vaccines, recombinant proteins, and silk-based proteins have revolutionised the sericultural sector (Nguyen *et al.,* 2019). This scales up the process of pharmaceutical protein production in a cost-effective manner.

MICROCOCOONS

Micrococoons are small cocoons of micron-scale comprising of a tough outer shell made up of nano-fibrils that encase a fluid at the centre. They are synthesized from the silk-spinning glands of *B. mori* V instar larvae yet to spin a cocoon (Laity *et al.,* 2015). The native silk obtained is subjected to a microfluidic strategy to generate robust bioactive materials of micron-scale as microcapsules or micrococoons that are prone to aggregation and favour long-term storage. Other materials that are incorporated to develop micrococoons are fluorinert FC-70 and amide surfactants. The silk gland is dissected using a microscope and the epithelial membrane is removed with forceps in cold distilled water instantly to prevent the dissolution of gland contents. The anterior and posterior portions of the gland are discarded to produce native silk cocoons. The diameter of the micrococoons fabricated was standardised to be 20mm. (Shimanovich *et al.,* 2017). Hydrogels, films, coatings, and 3D matrices are fabricated from the silk nanoparticles (Solomun *et al.,* 2020). Silk nanoparticles aid in the directed delivery of drugs and tumor destruction (Mottagithalab *et al.,* 2015) proving their systemic route of action.

PROFITABILITY OF MICROCOCOONS

In systemic drug delivery. The active functional groups of the amino acid residues of the fibroin protein as hydroxyl, carboxyl, amine, thiol, etc suitably bind with antibiotics and drugs, ensuring the targeted delivery of biomolecules and managing to protect and retain their biomedical properties over a considerable period (Phama and Tiyaboonchaia 2020). Therefore, small molecules after effective binding with fibroin functional groups are delivered to specific target sites efficiently.

Delivery of proteins molecules. Enzymes are proteins that are extremely essential for cell and tissue proliferation, growth, and differentiation. Therapeutic growth factors are also vital for cell and tissue development and wound healing. The commercially available microcapsules come with many disadvantages as low enzyme stability and faster degradation, limited power of penetration across biological membranes, low entrapment of biomolecules, and potential side-effects. However, fibroin nanoparticles serve as a vehicle for therapeutic protein delivery. Micrococoons have utility in site-specific delivery of proteins such as bovine serum albumin (Chen *et al.*, 2018), β-glucosidase (Cao *et al.*, 2014), and other essential growth factors.

Gene delivery. Fibroin nanoparticles have high transfection efficiency and specificity that results in site-directed transport of genes and gene sequences in a living system. Poly L-Lysine sequences incorporated into the fibroin nanoparticles resulted in high transfection of plasmid DNA to HEKC cells proving the role of micrococoons as a vehicle for gene transfer (Numata *et al.*, 2009).

Vaccine delivery. Vaccination is the method of injecting toxins or poisons to serve as antigens at sublethal doses that favors the production of antibodies at the time of real infection against a more virulent pathogen, thus strengthening the immunity of the organism. Most of the vaccines are thermos-degradable and expensive. Fibroin nanoparticles are potential vaccine delivery agents that maintain the stability of the vaccine and improve their specificity to act on harmful antigens (Phama and Tiyaboonchaia 2020). Micrococoons retain the stability and therapeutic properties of vaccines (Shimanovich *et al.*, 2017) and antibodies enhancing their action against several neuro-degradative diseases.

Delivery of ocular drugs. Cornea is an extremely sensitive part of the human body and the ocular drug delivery is a high skill among pharma professionals. The ocular drug, ibuprofen, packed in liposomes and enclosed in silk fibroin nanoparticles resulted in higher adhesion with human corneal cells (Dong *et al.,* 2015). The rate of release and penetration can be altered depending on the need by altering the concentration of fibroin nanoparticles. Therefore, micrococoons are potential delivery agents of drugs used to cure ocular diseases (Tran *et al.*, 2018).

Treatment of osteomyelitis. Research on the treatment of osteomyelitis is still inits infancy. At the same time, the use of fibroin nanoparticles having biocompatible and bio-degradable properties with no toxic side effects enhances the overall retention time of the drug molecule over the affected area (Phama and Tiyaboonchaia 2020). Slow and directed release of antibiotic vancomycin is by far proposed to be the best method to treat osteomyelitis (Zhou *et al.,* 2011).

Dermatological applications. Fibroin nanoparticles because of their amphiphilic nature have excellent transdermal permeation (Filon *et al.,* 2015) ability serving as potential candidates for drug delivery via transdermal surfaces. Micrococoons with curcumin (from turmeric) incorporated had high transdermal delivery efficiency compared to other such synthetic models (Mao *et al.,* 2017). Silk fibroin-based biomaterials such as hydrogels, films, membranes, yarns, sponges, scaffolds, fibers, etc help in cell repair, regeneration, and proliferation that helps in tissue development (Wang *et al.,* 2018). 3D fibroin scaffolds are highly efficient biomaterials for musculoskeletal and connective tissue regeneration. Thus, micrococoons or silk fibroin-based nanoparticles have the potential to regenerate skin and muscles after a burn or fire hazard (Shimanovich *et al.,* 2017).

Cure neurodegenerative diseases. Neurodegenerative disorders such as Alzheimer and Parkinsonism are critical conditions that result due to protein deformations and misfolding (Yonesi *et al.,* 2021). Micrococoons by their ability to stabilize the antibodies over a long time, improve their permeation to specific sites and controlled release of antibodies or vaccines are useful to treat neurodegenerative disorders that result in high human mortality each year. Current research exploits the potential of micrococoon loaded antibody to target protein α-synuclein which is a protagonist in the development of Parkinsonism (Shimanovich *et al.,* 2017).

APPLICABILITY OF SILK PROTEINS: SERICIN AND FIBROIN

Sericin and fibroin are the two main proteins present in the silk secreted by *B. mori*. The silk is originally secreted in liquid form that later hardens to form fibers. Fibroin is the core protein and one fiber is produced from each silk gland by the worm. The two fibroin strands are held together by a gummy, hydrophilic adhesive called sericin (Poza *et al.,* 2002).

POTENTIAL APPLICATIONS OF SILK SERICIN

Sericin, the gummy substance that binds the fibroin fibers together is a globular protein with random coils and β-sheets. It is highly hydrophilic and is thus washed-out during degumming to yield silk fibers. The protein has a molecular weight ranging from 20-400 KDa with nearly 18 amino acid residues (Zhou *et al.*, 2000). The greatness lies in the fact that polar functional groups such as carboxyl, hydroxyl, and amine groups enable the sericin to react with numerous biomolecules leading to polymerization, cross-linking, and combinations that make sericin a unique bioactive material for food, pharmaceutical, cosmetic, and other industries (Aramwit *et al.*, 2009).

Immunological response. Sericin is known to promote cell and tissue proliferation and generates compounds that inhibit tumour development (Aramwit *et al.*, 2009). The increase in the production of these localised cytokinin however did not induce inflammatory responses. Thus, the application of sericin creams accelerates the process of wound healing without producing inflammatory responses in organisms (Lamboni *et al.*, 2015).

Anti-oxidant activity. Sericin is considered an excellent source of anti-oxidants due to the accumulation of various flavonoids and carotenoids (Kurioka *et al.*, 2002) that scavenges the free-radicle formation and development of reactive oxygen species (ROS). Sericin inhibits the activity of the enzyme tyrosinase, which is a vital link in the process of skin melanization, thus sericin is a prime component of various skin-whitening creams and cosmetics. Silk sericin is known to suppress lipid peroxidation. The anti-oxidant property of sericin prevents the ROS-mediated oxidative damage to the midgut epithelial cells of *B. mori* (Micheal and Subramanyam 2014). The antioxidant activity of silk sericin is represented in Fig. 1.

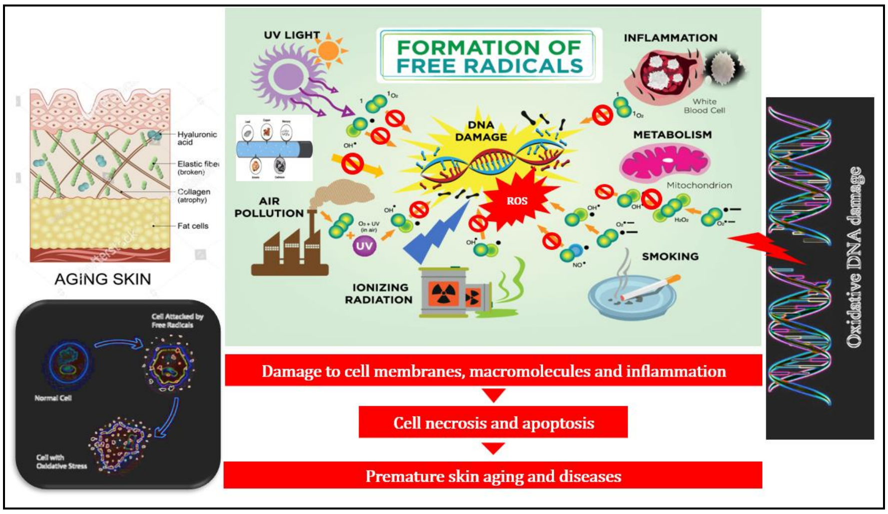

Fig. 1. Anti-oxidant activity of silk sericin preventing cell apoptosis and DNA damage. The figure represents various sources of ROS (Reactive Oxygen Species) generation and utility of sericin in preventing ROS mediated cell apoptosis.

Component of cosmetics. Sericin as a formulation of cosmetics possesses anti-irritant, anti-aging, anti-oxidant, and anti-wrinkle properties and is used in many creams, lotions, shampoos, moisturizers, lipsticks, ointments, etc. Sericin is a UV protectant and thus is a component of sunscreen lotions preventing damage to biomolecules of cells. It protects the skin from drying and dullness, and nails from becoming chaffy and brittle by the moisturizing action of hydrophilic amino acid residues such as serine. The protein also limits trans-epidermal water loss. The application of sericin-based lotions is known to heal and soothe the skin through their moisturising action (Patel and Modasiya 2011). Sericin can easily saturate into human skin and revitalize dead cells (Padamwar *et al.,* 2005). The water absorbing properties of sericin promotes its use in the development of contact lenses and artificial skin. Sericin is also utilized for the manufacture of foam-forming shaving gels, powders, and dermatitis-inhibiting formulations (Gulrajani, 2005).

Component of culture media. The cell proliferating properties of sericin make it a suitable constituent of the culture media intended for the multiplication of mammalian cells. It also improves cell viability in the culture media and promotes cell growth when used in optimum concentrations (Terada *et al.,* 2005). The properties of sericin do not degrade under conditions of autoclaving and thus the components of the culture media become chemically stable.

Wound healing properties. Sericin stimulates the production of collagen that progressively heals deep wounds (Aramwit and Sangcakul 2007). The serine residues in sericin are highly polar hydrophilic groups that facilitate the connection of sericin with the media. The incorporation of 8% sericin in the antibiotic creams as silver sulfadiazine serves as an excellent wound healing agent cutting down the hospitalization duration of the patients (Aramwit *et al.,* 2013).

Anti-tumour activity. The apoptic action of sericin makes it an excellent anti-tumor agent against colon cancer. It catalyzes the action of enzymes such as caspases that inhibits cancer cell proliferation and shuts down the action of anti-apoptic proteins in organisms (Kaewkorn *et al.*, 2012). Therefore, food additives and supplements are manufactured to fortify food items that fight tumors and cancers.

Sericin-based polyurethane foams. The foams formed by coating or incorporating sericin have higher water absorption and desorption rates (Minoura *et al.,* 1995). These hygroscopic moisture-releasing foams have good mechanical and thermal properties (Hatakeyama, 1996).

Anti-frosting action. Sericin films have anti-frosting action and are used on the surface of refrigerators and deep freezers, (Tanaka and Mizuno 2001) and vehicles with cold storage facilities. It also is used on roads and roofs of houses or as a spray over agricultural crops to prevent economic losses due to frost damage.

Sericin coats and polymer blends. Sericin coats promote the muti-functionality of articles. These articles do not dry up and have excellent water retention properties. Thus, sericin acts as a surface protectant. Additionally, sericin owing to its water-soluble nature mixes well with the polyvinyl alcohols imparting versatility, elasticity, and water absorption, and desorption potential to the polymer so manufactured (Yoshi *et al.,* 2000). Therefore, sericin hydrogel act as a soil ameliorant and have wound-healing potential.

Other uses. Sericin serves as a soil ameliorant, coagulates the debris in wastewater filtration systems, production of furniture and interior materials, as a food additive in the cooking of rice, fabric strengthening compositions, etc (Gulrajani, 2005). The biomedical utility of silk protein sericin reflects in the development of biocompatible sutures for surgical and clinical applications (Tsubouchi, 1999). All the essential application of silk sericin is summed up in Fig. 2.

Fig. 2. Applicability of silk sericin in **a.** Cosmetology **b.** tissue engineering **c.** Biomedical field **d.** Micrococoon delivery systems.

POTENTIAL APPLICATIONS OF SILK FIBROIN

Silk fibroin is the hydrophobic central protein comprising of heavy chain of 390-400 KDa and a light chain of 25-26 KDa linked together by the formation of disulfide bonds in a 1:1 ratio (Zhou *et al.*, 2000). It is abundant in glycine (43%), alanine (30%), and serine (12%) (Teuschl *et al.*, 2013).

Biological properties of fibroin. Fibroin, being the core silk protein shows excellent biocompatibility, high permeation rates through cells, tissues, and membranes, excellent penetrability to oxygen and moisture, lower negative side-effects, controllable release of vital biomolecules, good biodegradability, superior mechanical properties, low immunogenic response, potential anti-inflammatory biomaterial and has homeostatic properties. Thus, it is widely used in skin replacement, tissue and cell growth and engineering, regeneration of bone, cartilage, and cornea, and healing deep-seated wounds.

Anti-pathogen activity. Silk fibroin after sulphonation develops materials that ensure limited adsorption of HIV-1 particles to CD4+ cells inhibiting viral replication within the host (Gotoh *et al.*, 2000).

Non-woven mats. Electrospinning (spinning a polymer solution under the influence of a high electric field of 5-40 kV) or partial solubilization of natural silk fibers in 98% formic acid and $CaCl_2$yields non-woven silk mats that are effective in bone regeneration in humans and animals. Electrospun mats have utility in textiles manufacturing, electrode development, wound dressings and repairing, nerve guides, etc. (Yukseloglu *et al.*, 2015).

Fibroin films. Fibroin-based films are known to heal deep wounds with limited inflammatory response. They possess low surface flatness that ensures cell attachment and adhesion (Jin *et al.*, 2004).

Microspheres. Encapsulation in fatty acid of silk solution or phase separation with other polymers such as polyvinyl alcohol (PVA) yields silk microspheres (Rockwood *et al.*, 2011) that serve an enormity of functions. These microspheres are used as controlled release capsules of drugs or vaccines (Lan *et al.*, 2014).

Hydrogels. Hydrogels are networks of three-dimensional silk fibroin polymers that help in the delivery of cytokines and cell biomolecules. They have numerous applications as they resemble the soft tissues of the human body and can absorb and withhold organic liquid pollutants serving as effective depolluting agents (Hou *et al.*, 2018). They are prepared by the gelation of silk fibroin solution. The gelation can be done by physical (Van der Waals and Coulombic forces) (Rockwood *et al.*, 2011) or chemical process (formation of covalent bonds) (Nezhad-Mokhtari *et al.,* 2019). The rate of gelation of the fibroin solution depends on the temperature, pH, fibroin, and calcium concentration of the solution. High temperature, low pH, and increase in calcium and fibroin concentration, accelerates the silk fibroin gelation procedure. Osteoblast cells have good adherence and biocompatibility in 2% silk fibroin hydrogels. Cell proliferation in silk-based hydrogels was enhanced by the addition of 30% glycerol (Motta *et al.*, 2004). The development of controlled drug release tablets using silk fibroin is under investigation.

Aerogels. Replacement of the solvent component in the gels leads to the development of highly porous low-density material called aerogels (Xiong *et al.*, 2018). They are used in the manufacturing of pollution-free agents, biomaterial development, fire hazard retardants, insulators of thermal energy, etc (Mandal and Kundu 2009).

Sponges. Fibroin sponges are manufactured from silk fibroin solution. They are manufacturedusing the porogens (sugar crystals, mineral beads, salts, or any polymers), foaming with gas, and by the process of lyophilization (Meinel *et al.,* 2005). They can be formed by leaching of sodium chloride method or freeze casting method (Cai *et al.,* 2017). Fibroin sponges are used in tissue engineering as they are porous and help in cell adherence and proliferation. They also help in the delivery of nutrients and wastes. These scaffolds prove as excellent supporters for the regeneration of bone tissues (Bhattacharjee *et al.,* 2017).

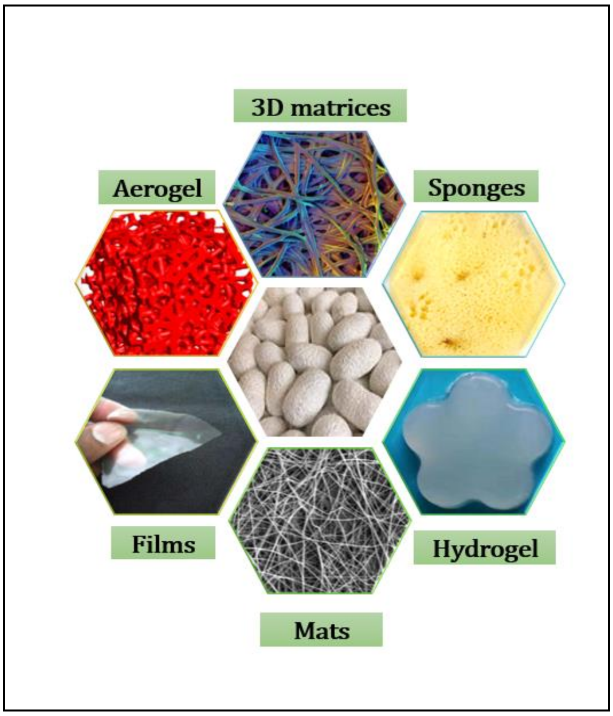

Fig. 3. The utility of silk fibroin in generation of composites as aerogels, 3D matrices, sponges, films, non-woven Electrospun mats, hydrogels etc.

Optics and photonics. The utility of silk fibroin in the arena of optics and photonics demands the development of silk fibroin solution developed by solubilizing the natural silk fibers in water, which resembles the solution secreted from the silk gland initially. Further processing of this highly versatile solution yields silk mats, sponges, gels, scaffolds, etc. that have pronounced utility in varied sectors. Silk films developed from the solution of native silk fibers are transparent and have very smooth surfaces (Applegate *et al.*, 2014). They are made by casting fibroin solution on a surface. The films are peeled off the surface as the water evaporates from the solution. The thickness of silk film so obtained can be altered varying the concentration and the solution volume before casting. The thickness of the self-assembled protein structure varies from nano to micrometres. Similarly, the silk solution cast on a substrate with varied patterns takes the shape of the mold as it dries. The evaporation of moisture from silk solution approximately takes 12-36 hrs under room conditions (Mehrotra *et al.,* 2019). This property is exploited to design various optical and photonic devices. Numerous fibroin composites are diagrammatically represented in Fig. 3.

APPLICABILITY OF SILK NANOPARTICLES

Microfluidics. It refers to the application of a small amount of fluids in channels of a narrow diameter of 10-100 µm. The microfluidic networks replicate the system of vascularisation in living systems ensuring the transport of blood, nutrients, and wastes within the scaffolds of silk. This area of silk microfluidics is well appreciated for tissue engineering, bone regeneration, and other similar applications.

Bioresists. Bipolar switching based on memory was investigated based on fibroin films. Scan tunneling microscopy was used to investigate the local conduction behavior at the nanoscale, which revealed a filamentary flipping process. Experts are hopeful concerning the versatility of using bioengineered silk-based Bioresists (with numerous variable material makeup adaptations) for micro/nanoscale bioelectric stimulation, "live" (real-time), as well as "in situ" cell micro/nano-manipulation (Hota *et al.*, 2012).

Sensing vapors. Organically extracted dyes were added to the solution of fibroin before they are electrospun to develop fibroin-based ecofriendly and biodegradable fluorescent nanofibers that behave as chemo/ biosensors. These sensors detect the hazardous and harmful fumes of concentrated acids such as HCl (Min *et al.*, 2018).

Biocatalyst. Silk fibroin-based nano matrices owing to their high surface adsorption and roughness have a high surface area for the adsorption or desorption of biocatalysts (Yi *et al.*, 2018).

Environmental applications. Silk fibroin-based nano-particles efficiently combat the heavy metal pollution of drinking and irrigation water, thus reflecting the importance of silk as a suitable biomaterial for the environment. For instance, uranium can be recovered from water using a silk fibroin solution (Aslani and Eral 1994). Fibroin membranes are also known to immobilize *Aspergillus niger* and *Pseudomonas fluorescence* cells (Demura*et al.*, 1989).

Filters to mitigate air pollution. Multilayered nano-fiber membranes developed using silk fibroin screen the pollutants from the air, purifying it before release into the environment. This system of air purification was more efficient as compared to the commercially used air purification systems to eliminate particulate matter as HEPA filters. This can reduce the plastic consumption for the manufacture of filters and improve air quality at the same time (Min *et al.*, 2018).

APPLICABILITY OF SILK-BASED NANOPARTICLES IN THE FIELD OF BIO-NANOTECHNOLOGY

Bio-nanotechnology is the field that encompasses biology, nanotechnology, bioengineering, and bio-medical, all of which integrate to fabricate products with novel application and high standard of commercial use.

Tissue engineering. The biocompatibility, biodegradability, and mechanical properties of bio-material silk resemble those of 3D extracellular tissue matrix, which makes silk-based fabrications an ideal alternative to synthetic nano-structures in tissue engineering. The silk scaffolds and hydrogels also match cellular topology and morphology and thus serve as templates for the engineering of tissues that are structurally aligned. Therefore, silk scaffolds, silk hydrogels, etc can be appropriately used in engineering damaged tissues as it supports cell growth, adherence, and proliferation, and tune well with other secondary growth factors and promoters facilitating magnification of somatic cells in a directed manner for more than 3 weeks (Altman *et al.*, 2003). A combination of Recombinant human-like collagen and silk protein fibroin is known to yield a suitable biomaterial useful for the engineering of hepatic tissues.

Nanostructured optics. Silk is an excellent biomaterial owing to its surface transparency and superior mechanical and biodegradable properties. Bio optic and photonics application of silk fibroin solution can be well explored by the utilization of silk films to replicate cellular and tissue topology and orientation at the nano-scale. For instance, for flexible optoelectronics, ZnO nanorod array hybrid photo-detectors on Au nanoparticle-embedded silk protein were created (Keten *et al.*, 2010).

Electronics. Flexible silk-based electronic devices are fabricated to assay the electrical impulses of pivotal organs such as the heart, brain, and muscles. Thus, the application of silk based high-efficiency bio-materials for developing integrated bio-electronic devices (Huang *et al.*, 2018) can perform numerous biomedical and clinical diagnosis functions that may be a boon for humankind.

Silk nanofibrils for water purification. Silk fibrils-based multilayered water purification systems act as a molecular sieve to strain out nano-size particles and harmful nano-biomolecules from entering human biological systems. The fabricated silk-based water purification systems have high water-permeable membranes that efficiently strain out unwanted dyes, heavy metals, and proteins (Ling *et al.*, 2017). Therefore, these architects prove to be superior over commercially available multilayered membrane-based water purification systems.

CONCLUSIONS

Silk is a widely used biomaterial owing to its high biocompatibility, biodegradability leading to formation of harmless by-products, excellent mechanical, and tensile properties, low or no immunogenic or inflammatory response, no negative side effects, etc. All these attributes make silk and its proteins a suitable choice for various bio-medical applications such as tissue engineering, bone regeneration, and macromolecule delivery to the target site. Apart from the above-cited advantages, efficiently extracting silk from wastewater effluents curtails the pollution load from the sericultural sector. Sericin and fibroin as mentioned throughout the review have many potential biomedical applications that can be further explored. Silk micrococoons serve as effective vehicles of delivery for genes, proteins, small molecules, drugs, and vaccines. Silk as a bio-active compound also diminishes the instance of various neurodegenerative and ocular disorders. Current research concerning the utility and applicability of silk and secondary products of sericultural industries sheds light on the versatility of silk as a biomaterial. Further research on the utility of silk-based nanostructures in varied sectors can yield economic products of commercial importance and serve as milestone achievements in life science.

FUTURE SCOPE

Silk bio-nanoparticles have excellent versatility and are a favored choice in textile manufacturing, tissue engineering, regenerative medicine (bone, cartilage, tissue, nerve, skin, etc.), pollution retardants, cosmetology, and various industrial applications. However, issues regarding prolonged storage and retainment of the mechanical properties of silk nano-bio-composites deserve further investigation. Clinical trials and vigorous investigation procedures can further enhance the utility of this emerging field which is still in its infancy.

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Conflicts of Interest. None.

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