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From Earth to Orbit: The Versatility of Silk in Space, Medicine and Eco-Innovation

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Abstract

The cocoons of mulberry silk worm, *Bombyx mori* is the source of a natural protein called fibroin which has transitioned the traditional textiles to a multifaceted material in science and technology for energy storage, biodegradable packaging and smart textiles. Now-a-days it is used in aerospace and electronics engineering, medicine industry as it is exceptionally biodegradable, thermally stable, biocompatible and it also has high tensile strength and molecular tenability. All these characters empower the use of silk fibroins in various industries to obtain energy in a sustainable manner. Unlike other fabrics, silk fibroin has shown remarkable cryogenic stability and it offers resistance against any kind of tearing and brittleness in freezing space environment. In health care units these silk fibroins are used in tissue engineering, drug delivery and for healing of the wounds. Hence, silk is a commendable eco-friendly material to address the global technology and environmental changes.

Keywords: Biomedical engineering, Nanocomposites, Silk fibroin, Space materials

Introduction

Silk is a natural polymer obtained from the cocoons of silk worm, *Bombyx mori* which is available widely in comparison to cellulose, chitosan and collagen. It was widely used by the people of China and Indus Valley during 2500 BCE as a symbol of luxurious textile material which later on lead to the development of Silk Road to serve as platform for global trading (Vainker, 2004). It has two proteins such as fibroin (72-81%) and sericin (19-28%). Silk fibroin contains many nanoscale fibrils which are arranged to form the microfibrils, which enhances the durability of silk (Tao *et al*., 2012).

Silk is renowned as the 'queen of textiles' due to its natural luster, softness, strength, dye adaptability, breathability and climate comfort, silk remains a staple in the textile industry. Each year, global production exceeds 120,000 metric tons, with China, India and Japan serving as the primary producers (Pereira *et al*., 2015). However, beyond its historical and aesthetic significance, silk has gained scientific prominence for its remarkable molecular architecture and functional flexibility (Figure 1). This article highlights the

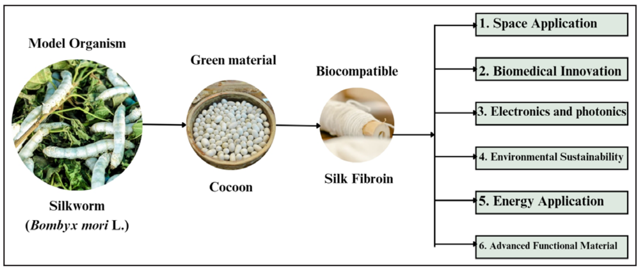

Figure 1: Schematic representation of SF main applications

diverse and emerging applications of silk fibroin in space technology, biomedicine, flexible electronics, energy systems, environmental sustainability and advanced functional materials, emphasizing its potential as a green, scalable and multifunctional biomaterial.

Application of Silk in Space: From Cocoons to Cosmos

In aerospace engineering, silk has shown exceptional adaptability under extreme conditions, particularly at cryogenic temperatures. Unlike most synthetic polymers, silk fibres maintain flexibility and toughness at -200 °C due to

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their hierarchical nanofibrillar structure, making them ideal for spacecraft and space suit components. Its internal nano-scale fibrils dissipate energy and prevent crack propagation, enhancing durability against micro-meteoroid impacts (Choi *et al*., 2018). Silk composites are also effective for ultraviolet shielding and thermal insulation due to their low weight and resistance to brittleness in freezing environments. Additionally, silk enhances astronaut gear by offering thermal regulation, impact resistance and moisture-wicking comfort during long missions (Figure 2). Advanced space suits are increasingly incorporating silk in multi-layered systems to enhance mobility and protection against thermal extremes. Additionally, silk's integration into aerospace composites, especially those functionalized with nanoparticles offers potential for radiation shielding in long-duration missions. It can be also suitable for the preparation of high-altitude aircraft as well as different polar research equipment due to its high strength to weight ratio.

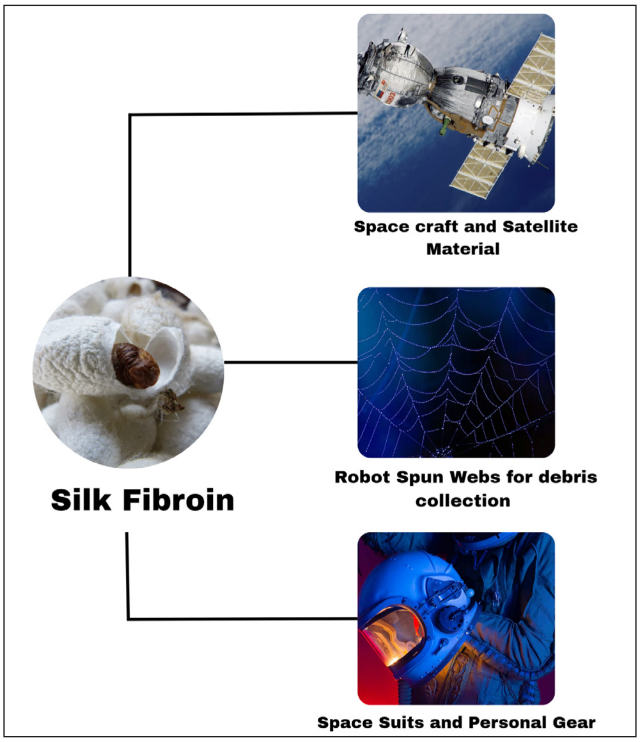

Figure 2: Applications of silk in space

Other High-Tech Applications

1. Biomedical Innovations

The silk protein fibroin, *i.e.*, derived from the silkworm *Bombyx mori* is widely used in different biomedical applications. Variable properties of silk protein such as good mechanical strength, biocompatibility, biodegradability *etc*. help for the preparation of different processed equipments such as scaffolds, hydrogels, films, fibres which can be used for the cell adhesion, tissue regeneration as well as various biomedical applications.

2. Bone Tissue Regeneration

The silk protein, Fibroin is combined with different ceramics such as beta-tricalcium phosphate and hydroxyapatite to form scaffolds that can be similar to natural bone structure. Different additives, proteins and trace elements are used to improve the mineralization and osteogenic differentiation. Hydrogels contain antimicrobial nanoparticles which help to prevent different microbial infections.

3. Cartilage Tissue Regeneration

The scaffolds that prepared from silk protein help the growth of chondrocytes and repair the cartilage. The collagen materials enhance the growth factor responsiveness while certain natural compounds such as curcumin is having anti-inflammatory characteristics. Gene delivery through Silk Fibroin gelatine hydrogels helps for the regeneration of cartilage and prominent for osteoarthritis therapy.

4. Cardiovascular Regeneration

Fibroin is combined with peptides and polymers such as hyaluronic acid which can be effective against vascular grafts. The scaffolds derived from SF help in the growth of epithelial cells near heart and also repair the myocardial.

5. Skin Tissue Regeneration

The nanofibril structure of SF supports the wound healing and skin tissue regeneration. Silk fibroin is biocompatible in nature due to which it can be used as a substitute for synthetic skin. It has greater mechanical strength and it also provides good resistance against moisture.

6. Neural Tissue Regeneration

Silk fibroin when integrated with some conductive materials like graphene oxide, carbon nanofibres and polypyrrole helps in improving nerve conduction and neural signalling. Hydrogels enable controlled release of neurotrophic factors for spinal cord and brain repair. It helps in lowering the oxidative stress generated during nerve disorders and provides protection to the nerve cells of central nervous system.

Other Biomedical Applications

- *Breast Implants*: Silk fibroin helps in drug delivery to the targeted organ and regeneration of the adipose tissue. It also helps in hyperthermia-based tumour therapy by using magnetic nanoparticles (Zhang *et al*., 2024).
- *Hernia Repair*: Silk fibroin when integrated with chitosan and polypropylene helps in reduction of adhesion and improves the healing process smoothly.
- *Sutures*: Many evolutionary improvements have been carried out in traditional silk sutures to prevent bacterial infection and better healing by blending it with antimicrobial coatings (Figure 3).

1. Flexible Electronics and Photonics

The role of silk fibres in flexible electronics has led to the development of biodegradable sensors, implantable devices and electronic skins, leveraging silk's mechanical durability and controlled biodegradability. Flexible electronics have transformed modern technology, enabling innovations in electronic skins, wearable sensors, flexible displays and actuators across healthcare, energy, defence and communication sectors. They adapt the curved and dynamic surfaces that can increase the possible applications. The

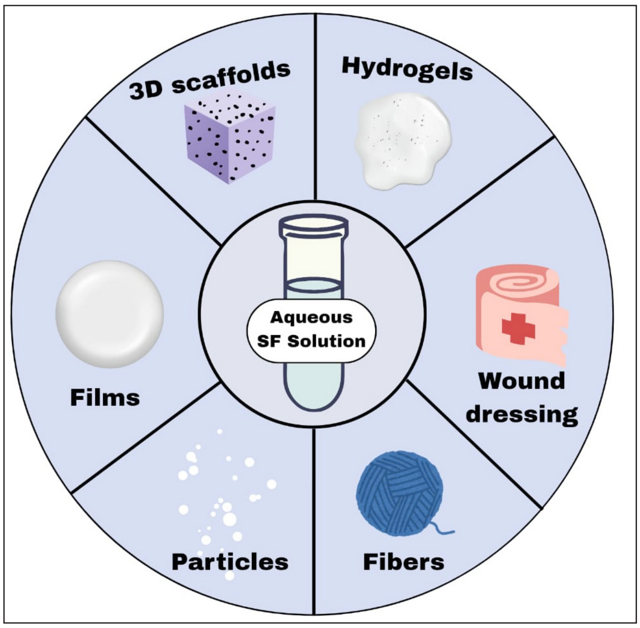

Figure 3: SF as a functional biomaterial for the biomedical field

silk protein acts as an ideal material for the preparation of flexible electronics due to its versatile characteristics. The spider silk is having good mechanical strength that can be favoured for scalability. It consists of 70-80% of fibroin and 20-30% of sericin. Through different processing techniques such as ethanol, methanol, vapour annealing, the structure of silk fibroin can be adjusted. Electrospinning methods combined with polyethylene oxides blends to form a consistent structure of SF nanofibres. SF's stretchability and transparency develops different wearable electronics materials.

2. Environmental Sustainability

Silk is pondered as a sustainable material because it is highly biocompatible, biodegradable and eco-friendly. These qualities of silk make it suitable in different industries. In food processing industries, the silk has a prominent role. The silk protein can be used as edible coatings to regulate optimum moisture content and gas exchange on fresh products. It can increase the shelf life of the products without refrigeration or energy consumption. The protein creates a transparent and edible layer around the fruits such as apple, strawberry to prevent the moisture loss and microbial growth. It is reported that the strawberries that are coated with 1-2% of silk fibroin protein having good appearance, texture and firmness for a longer period of time than the uncoated strawberries. This coating can also be protected from oxidants and microbial growths). SF is being considered as eco-friendly coatings and adhesives for wood and paper that can provide biological alternatives against petrochemical-based products. In textiles, lab-grown silk reduces the resource intensity of conventional sericulture cutting down on land, water and labour demands while maintaining performance.

3. Energy Applications

Silk fibroin has a significant role in different energy technologies. It contributes different sensors, supercapacitors, electric nano-generators *etc*. It can be converted into flexible, translucent films that can be suitable for different bio-integrated electronics, wearables and energy devices. Different customizable circuits are prepared from these materials (Tao *et al*., 2012). For the storage of energy, carbonized fibroin combined with nitrogen and carbon having high surface area and more conductivity. These materials have replaced the traditional electrodes, with specific capacitance. Silk protein is also used in TENGs to produce mechanical energy from motion. Furthermore, silk's porous matrix structure supports enzyme immobilization in biobatteries and microbial fuel cells, improving electron transfer and stability.

Advanced Functional Materials

Silk fibroin acts as a base for developing advanced functional materials (AFMs), due to its biocompatibility and mechanical strength quality. It can be functionalized into programmable biomaterials, nanocomposites with graphene and used in soft robotics, optoelectronics, bioprinting and synthetic biology. Silk fibroin integrated with antimicrobial or ethylene absorbing layers plays a great role in improving shelf life of the crops and it also reduces the spoilage of the crops. They also enhance the productivity of the crop in green house conditions by converting harmful UV radiation in to photosynthetically active radiation (PAR).

Conclusion

The natural polymer "silk fibroin" has evolved tremendously to become the most suitable material from cocoons to cosmos to be incorporated in space composites, electronic devices and medical devices due to its biocompatibility and biodegradability. By the advanced technologies, silk offers an eco-friendly basement for the next generation technologies. In the fields of bio-medical, space innovation, sustainability, electronics, silk offers prominent opportunities. Silk fibre has the potential to revolutionise the development of biodegradable, flexible materials that can be promote environmental sustainability and technological advancement for a better research and innovations.

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