Chapter 11

Sericulture 4.0: Sustainable Silk through Modern Technology

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Abstract

This chapter investigates silk fibroin's (SF's) structural characteristics and capacity to produce composites with natural materials including curcumin, keratin, alginate, hydroxyapatite, hyaluronic acid, and cellulose. The study emphasizes silk's compatibility with natural additives due to its high number of polar functional moieties. The combination of silk and natural additives produces synergistic interactions, increasing material application while reducing individual unit restrictions. It also examines the present state and problems of commercializing silk-based biomedical devices. This section discusses current biomedical research on silk nano-biomaterials, with an emphasis on their applications in bio-cargo immobilization, chemo-biosensing, bioimaging, tissue engineering (TE), and regenerative medicine. It also explores the nanoscale attributes of silk, like nano-fluidics for specific blood types. The chapter also covers the limitations and opportunities for transforming silk nano-biomaterial research into affordable, off-the-shelf biomedical alternatives. This article examines at the complicated structure and characteristics of natural silk fibers, as well as their applications in biomedicine and smart fiber technologies. It highlights the application of silk fibers in multifunctional materials due to its mechanical strength, biocompatibility, and biodegradability. The study also discusses their biological applications, which include surgical sutures, TE, and drug delivery systems, as well as current advances in smart fiber applications such as sensing, optical technologies, and energy storage. This article looks at an eco-friendly process of making mulberry spun silk fabric that reduces environmental impact and waste. The silk business pollutes the natural environment by emitting dust, smells, and gasses, resulting in high production costs and material waste. The novel method employs silk waste to minimize carbon emissions, material waste, and energy use. The article examines silk and cotton fibers to see which is more successful in atmospheric deterioration.

Keywords

Silk Fibroin (SF), Biomaterial Engineering, Fiber Bioengineering, Regenerated SF (RSF), Piezopolymer, Piezoelectric, Sericin

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1. Introduction

Silk, sometimes known as the “queen of textiles,” is a sustainable biopolymer with exceptional biocompatibility, adjustable degradability, mechanical resilience, and simplicity of processing. Recent study into its nano-scale characteristics has broadened its biological uses, emphasizing its distinct role in biomaterial engineering [1]. Recent advances in silk materials have created new prospects for sustainable green energy, acting as an environmentally benign alternative to existing energy harvesters and storage devices. Silk-based energy sources are viewed as novel possibilities for flexible human-integrated applications because to their biocompatibility, biodegradability, and appealing features as a result of natural protein composition, modification methods, large-scale green manufacturing, and advanced fabrication processes [2]. Natural silk fibers are attractive for biomedical applications and smart fiber technology because of their ease of use, high mechanical qualities, varied functional groups, controlled structure, and exceptional biocompatibility. These fibers provide environmental sustainability, biocompatibility, and biodegradability, making them indispensable in modern materials science and technology, promoting the development of next-generation smart materials [3]. Due to the complexities of human lifestyles, there is a rising demand for functionalized textile materials. Nonetheless, the production processes have a detrimental environmental impact. A potential alternative is bio-mimicry, which employs chemical-intensive applications to transmit natural capabilities. While it shows promise for sustainable manufacturing, it must minimize hazardous chemical use and boost structural uses to obtain long-term results [4]. The silk textile industry's life cycle assessment (LCA), from extraction to fiber lifetime, aids in quantifying resource depletion and minimizing environmental consequences. The industrial sector contributes significantly to environmental damage. Spun silk is a type of silk that recycles waste materials at various stages. However, the spun silk sector faces significant challenges such as environmental pollution, low production efficiency, material waste, and energy exploitation [5]. Researchers are looking for greener technologies and materials due to the detrimental impacts of synthetic materials and chemicals on the environment and individuals. Silk fibroin (SF) is attracting scientific attention because to its exceptional toughness, tensile strength, biodegradability, Young's modulus, functional groups, simplicity of processing, and biocompatibility. Combining SF with natural materials might provide an alternative to chemical-based treatment methods, resulting in extensive study into silk-based biomaterials [6]. While textile production and processing processes offer desired features including stretch and moisture control, they also contribute to greenhouse gas emissions, micro-plastic contamination, and hazardous wastewater. Green alternatives, such as fiber bioengineering at the nano, micro, and macro-scales, can enhance the environmental effect and technical performance of textile materials, opening the path for a circular, sustainable economy [7]. Spun silk is a high-quality textile material with a high added value, made mostly from mulberry and non-mulberry silk waste, as well as eri silkworm cocoons. Due to market diversity, modern spinning processes are replacing traditional hand spinning. Mill spinning involves complex machinery and is employed to produce fine count silk yarn. This environmentally friendly technique is popular with ethical customers and has enormous research possibilities. Only a few commercial machinery are available for special silk spinning units [8]. Insects and arachnids create silky proteinic fiber with distinctive qualities including resistance, elasticity, stickiness, and toughness. Because of its low density, degradability, and adaptability, this fiber offers biomaterial application promise. Electro-spinning enables the development of nano-metric-scale nonwoven mats with unparalleled pore size and structure. Silk scaffolds are used in regenerative medicine, medication delivery, decontamination, and filtration. Silk is made by the silkworm Bombyx mori and the spiders Aranea diadematus and Nephila Clavipes [9].

2. Sustainable Silk through Modern Technology

Silk fibroin (SF), which is generated by the Bombyx mori L. silkworm, is an important biomaterial owing to its biocompatibility with humans, high mechanical strength, biodegradability, and physiologically active characteristics. SF has been employed in a variety of experiments to create sponges, hydrogels, nano-spheres, and films, resulting in important advances in tissue engineering and cancer treatment. Genetic engineering has also improved the characteristics of SF-derived biomaterials [10]. Natural silk fiber from the Bombyx mori silkworm is a premium raw material in the textile industry as well as a medical suture due to its great strength and flexibility. Regenerated SF (RSF), a protein derived from cocoons, has recently acquired popularity due to its simplicity of processing, improved biocompatibility, regulated biodegradation, and versatility of functionalization. This has resulted in substantial attempts to convert silk fibroin into sophisticated materials for biomedical uses, flexible optics, electronics, and filtration [11]. The usage of biologically based materials and their incorporation into living technologies may create a business opportunity for natural biopolymers. Biopolymers incorporated into implantable devices or in vitro chips for electrophysiological recording of brain cells are in increasing demand for neurological applications and neuroscience research. Bombyx Mori produces silk fibroin, a natural protein biopolymer that has uses in organic photonics, electronics, and optoelectronics. The development of silk-based material interfaces and devices aimed at bidirectional communication with brain cells is being evaluated [12]. Silk biomaterials, including particles, coatings, and assemblies, are distinct materials with diverse sizes and dimensions. These multi-scale SF materials offer adjustable architectures, outstanding mechanical characteristics, and biocompatibility, making them indispensable for biomedical and drug delivery applications. In addition to their adjustable architectures and great biocompatibility, they can be beneficial in a variety of applications [13]. SF holds promise a new generation of soft bioelectronics due to its excellent biocompatibility, tailorable biodegradability, and an impressive set of mechanical properties. Silk's adaptability in numerous material forms enables integration with implanted sensors and electronics. Currently, silk has dominated the development of resorbable surfaces for in vivo applications. However, the development of non-transient water-stable silk bio-electronics necessitates multidisciplinary methodologies for non-resorbable packaging. This intersection of demand, know-how, and potential influence on implantable applications demonstrates the enormous potential of silk in bionic relationships [14]. Silk, a natural proteinaceous substance made from fibroin and sericin, has been utilized in interior design and architecture. Researchers are combining silk's active qualities into SF to improve uniformity, paint strength, coatability, and portability. Plasma therapy can also enhance silk characteristics more quickly, resulting in active silk with attributes suited for both new and established fields. Various plasma treatments can yield active silk, which has potential in interior design and architecture [15]. The increased demand for wearable healthcare monitoring devices requires bioelectronics production that is sustainable. Green electronics seeks to replace inorganic battery-powered devices with organic, biodegradable solutions. Silk, a green material with adjustable biodegradability and flexibility, is being investigated for its usage in functional electronics due to its inherent piezoelectricity. This idea is gaining traction in the scientific and industrial communities [16]. Wearable piezoelectric sensors depends heavily on the biosafety and sustainability of inorganic perovskites and organic piezopolymers. Because of its biocompatibility and adjustable characteristics, SF is an appealing option. However, its natural piezoelectricity is minimal, limiting its practical sensing applications. SF sensors can detect joint bending and muscle movements in people, making them appropriate for wearable bio-electronics applications [17]. Piezoelectric materials derived from biological sources are rapidly being investigated because to their biocompatibility, sustainability, and capacity to adjust features through chemical modification and genetic engineering. Silk, a bio-piezopolymer generated from silkworm glands, has been intensively explored for its piezoelectric characteristics. A thorough material characterization technique was performed to evaluate the performance of a thin film produced from a silk-Aloe vera composite solution. The composite material increased piezoelectric properties, had high surface uniformity and crystallinity, and was employed in pressure sensors [18]. The expanding population and disposable goods trend, notably in the textiles sector, exacerbates the worldwide oversupply dilemma. Demand for quick fashion is strong, resulting in the depletion of non-renewable feedstocks and strain on natural fiber supply. To remedy this, we should look at our history for sustainable textile production methods. Research on regenerated protein fibers reveals the resource potential of food waste, however current manufacturing processes provide obstacles for a circular economy owing to hazardous waste creation [19]. Inadequate waste water treatment in businesses, agriculture, and homes poses a serious hazard to the ecology and human health. Traditional materials have been employed to eliminate contaminants and repurpose water resources. However, due to post-use degradation hurdles and environmental compatibility issues, natural biopolymers such as silk protein have gained popularity for their environmental friendliness, low carbon emissions, biodegradability, sustainability, and biocompatibility [20].

3. Recommendations

Based on our thorough literature review, we propose the following recommendations for the future.

- Despite substantial advances in SF-based materials, large-scale SF synthesis and nano-structure control remained significant challenges. The majority of SF materials-processing procedures are laborious and solvent bulky, and increasing hierarchical structure control for particular applications continues to be an issue.
- SF, a biomaterial that has made major advances to tissue engineering, is additionally employed in cancer treatment as a coating agent for lung and breast cancer. Molecular engineering has been exploited to improve SF for biological purposes.
- The polymer's promise for healthcare disciplines is apparent, with its increasing exposure and electro-spinning technology anticipated to inspire an abundance of initiatives in the future.
- Silk research, involving electro spinning, has resulted in nano-metric scale spinning mats for building scaffolds with precise topographies or complex embedments. However, producing an electrospinning dope from fibroin is problematic because to the gathering and handling of natural silk, which is difficult for unfarmable spiders, or regeneration using genetically engineered vectors.
- Spideroin is an innovative biopolymer with high strength, elasticity, biocompatibility, durability, and low density that competes with high-performance materials. Its distinct profile and capacity to conduct novel behaviors such as super-contraction and water-tailoring distinguish it as a one-of-a-kind and outstanding material.
- The availability of protein feedstock for textile goods, notably milk manufacturing, must be carefully considered owing to possible valorisation back into the food sector. This creates environmental, sociological, and economic concerns that must be extensively investigated in order to establish the best avenues for valorisation while balancing human nutrition and lowering the environmental effect of accelerating fashion.

- Ethical and local textile sourcing, rather than outsourcing, improves environmental benefits, gives businesses more control over manufacturing, and increases worker well-being, hence minimizing the need for outsourcing.
- Waste streams can lower fermentative bio-fabrication costs, but understanding the unpredictability of waste stream inputs and the repeatability of bio-based fiber processing is critical for moving the circular economy forward.

Conclusion

Fibroin, an ancient natural fiber with outstanding strength and flexibility, has a distinct structure, according to research. This semi-crystalline long chain of amino acids is very resilient to strain pressures and can adapt to a variety of situations. Spider silk is the most inspirational of the three, known for its biocompatibility, availability, and simplicity of manipulation, whereas silkworm silk is praised for its biocompatibility. SF-based materials are appealing biomaterials because of their distinct structure, low weight, outstanding mechanical capabilities, flexibility, optical transparency, thermal stability, biocompatibility, controlled biodegradability, variety in material format design, and mild aqueous processing. Green technology for extracting and fabricating reverse-engineered SF have been developed for medicinal, electrical, optical, and filtration use. Bio nanotechnology, including nano-imprinting, patterning, restricted alignment, and 3D printing, can help to accelerate the development of SF-based materials for a variety of applications. SF, a protein produced by B. mori, is a primary structural component of silk and possesses unique qualities such as biocompatibility with human beings, mechanical properties, and biodegradability. Its promise in medicine has resulted in breakthroughs in biomaterials including scaffolds and nanoparticles. SF's properties may be regulated and reconstructed using a variety of ways, and it has earned recognition as a green material due to its promise in a variety of applications. For enhanced environmental performance and circularity, the work advises reusing waste and byproduct streams, creating efficient fiber processing, employing perfluorinated, formaldehyde, and metal-free chemicals, and recycling solvents. Renewable energy sources should also be employed to make bio-fabricated textile fibers. Step-by-step improvements should be supported by a third-party LCA, which should be incorporated into environmental performance measures and industry certifications. The study describes a composite bio piezopolymer that incorporates silk fibroin solution and Aloe vera extracts, resulting in enhanced performance and homogeneity. This composite may be a viable alternative to traditional piezoelectric materials, as evidenced by the fabrication and characterization of a pressure sensor. Thin films might be employed in transducers, energy harvesters, and self-powered systems, proving their practicality.

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