Chapter 10

The Future of Silk: Integrating Technology with Sericulture

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Abstract

Silk Fibroin (SF) is a versatile material that can be reconfigured into a variety of shapes like films, carpets, hydrogels, and sponges using a variety of processes. Recent advances in fabrication techniques, including as micro-patterning and bio-printing, have enabled the development of sophisticated SF-based scaffolds. These scaffolds have uses in bone, cartilage, ligament, tendon, skin, wound healing, and the tympanic membrane, with future opportunities and difficulties to address. This study examines the functional features of SF, including di-electricity, piezoelectricity, electron loss, and environmental sensitivity. It discusses silk fibroin preparation procedures as well as current advancements in its application as a basic material. The study also examines advanced works that use silk fibroin as functional components, as well as the limitations and future directions of silk fibroin-based flexible electronics. The study investigates the use of SF as a wound dressing, its efficacy in both in vitro and in vivo conditions, and its potential uses in the treatment of chronic and acute wounds, including burns. Sponge, hydrogels, nano-fibrous matrices, scaffolds, micro/nanoparticles, and films are all examples of biomaterials containing SF and its derivatives. To offer a thorough grasp of the issue, the study compares SF-based therapies to other natural polymers. This article gives a detailed summary of the current state of development for functional silk protein hydrogel. It discusses the cross-linking processes, characteristics, benefits, and limits of various hydrogels. The article also covers other forms of hydrogels, such as high strength, injectable, self-healing, adhesive, conductive, and 3D printable. The hydrogels' applications in tissue engineering, sustained medication release, wound healing, adhesives, and bioelectronics are discussed. The development opportunities and constraints of silk protein functional hydrogels are also discussed. The study's goal is to contribute to future innovation by encouraging logical design of novel mechanisms and the effective implementation of target applications.

Keywords

Silk Fibroin (SF), 3D Bio-Printing, Hydrogels, Bio-Ink, Bombyx Mori, Flexible Electronics

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1. Introduction

Silk, with its unique hierarchical structure, has extraordinary material characteristics and biological capabilities. It may be utilized to develop high-performance, multifunctional, and biocompatible materials with careful design. Computational modeling has been utilized to better understand silk's mechanical characteristics, anticipate its biomaterial qualities, and devise innovative production methods. Fine-scale modeling, mostly through all-atom and coarse-grained molecular dynamics simulations, offers an in-depth analysis of silk [1]. Silk fibers are unique materials because of their hierarchical structure and biological processes. Their biocompatibility and outstanding mechanical qualities have made them useful in a variety of technological and medicinal applications. Recent computational modeling has brought out the relationship between molecular architecture and emergent characteristics, revealing predictive power in research on novel biomaterials [2]. Silk fibroin (SF), made from Bombyx mori silkworm cocoons, have been used in fabrics and suture materials for decades. It has recently been employed as a wound dressing since it has its beneficial biological and mechanical features, which include mechanical rigidity, flexibility, biocompatibility, biodegradability, water vapor permeability, and mild antibacterial capabilities [3]. SF hydrogels have received much attention due to their assurance, biocompatibility, regulated degradation, and prospective applications in biomedicine and other sectors. However, typical silk protein hydrogels have a basic network structure and a specific function, making them less adaptable to complex surroundings. The creation of functional silk protein hydrogels has created chances to bypass these constraints, and their functional design and prospective uses have sparked global interest. This has sparked greater interest in the creation of silk protein hydrogels [4]. The design and manufacture of hydrogel materials, particularly silk proteins, has piqued attention because to their biological properties and promise in biomedicine. These natural resources may be used in hydrogels, providing value to natural resources while satisfying green production requirements, demonstrating the benefits of the 'asynchronous economization' manufacturing sector. This multidisciplinary approach is critical for a wide range of hydrogel applications [5]. A potential bio-inspired technique entails removing required silk building pieces and reassembling them into functional regenerated silk fibroin (RSF) materials with programmable formats and architectures. This method has good processing and adaptability, making it suitable for a wide range of biological applications. Novel extraction and restoration procedures have been developed to create RSF materials with similar characteristics [6]. Photo cross-linkable biopolymers are prominent in biomedical applications because of their simplicity of production, adaptability, and variety of possibilities. Silk, which is highly biocompatible, minimally immunogenic, and adjustable, has the potential to be a biomaterial in its photo-polymerizable state and mixes with other photo-curable polymers [7]. Bacterial contamination of biomaterials is a global health hazard. The creation of multifunctional biomaterials with antibacterial characteristics is an ongoing objective in biomedical applications. Due to its unusual mechanical characteristics, biocompatibility, adjustable biodegradation, and diverse material forms, SF is an extensively researched natural polymer authorized by the US Food and Drug Administration [8].

2. The Future of Silk: Integrating Technology with Sericulture

Silk fibroin (SF), the major protein that constitutes silkworm silk, has been used in a variety of high-tech applications other than textiles, including biomaterials for drug delivery and tissue engineering. Its superior mechanical features, such as processing capabilities, biological compatibility, predictable biodegradation, and diverse functionalization, have made it a valuable asset [9]. SF, a promising candidate for next-generation flexible electronics, is gaining popularity due to its superior biocompatibility and biodegradability, as well as desirable properties such as adjustable water solubility, optical transmittance, high mechanical robustness, light weight, and ease of processing. These characteristics make SF an important component in the development of biocompatible flexible electronics, particularly wearable and implantable devices, which are frequently absent in other biological materials [10]. SF has emerged as a key material in tissue engineering (TE) during the last two decades, with applications spanning from skeletons to neural regeneration. Due to its flexibility and simplicity of processing, a variety of materials have been developed to meet specific application requirements. Despite extensive research, barely a few fibroin-based medicinal items are employed in healthcare environments [11]. SF has applications in medical sectors including TE, regenerative medicine, medication delivery, and medical devices. Silk chemistry and biomaterial design advancements have resulted in the creation of novel silk-based materials and technologies. Selective chemistries could enhance silk properties involving mechanics, biodegradability, processing capacity, and biological interactions in order to address therapeutic complications [12]. TE is the process of blending cells, scaffold materials, and growth agents to regenerate or replace damaged tissue and organs. SF, a natural protein with outstanding mechanical, biodegradable, and biocompatibility qualities, is a common scaffold material for TE applications. SF may be reconfigured into a variety of material forms, including films, mats, hydrogels, and sponges, utilizing processes such as spin coating, electrospinning, freeze drying, and crosslinking. More sophisticated SF-based scaffolds are being researched employing high-precision methods like micro-patterning and bio-printing [13]. Biocompatibility, mechanical characteristics, biodegradability, as well as security are all reasons why SF is a prominent biomaterial. It was recently created as a medication carrier for cancer treatment, successfully destroying tumor cells with no side effects or drug resistance. However, few trials have been conducted on SF-based anticancer treatment. The evolution of SF-based medication delivery devices is emphasized [14]. Silk-based conductive materials are frequently employed in bio-interface applications that include artificial epidermal sensors, soft bioelectronics, and tissue, cell scaffolds. However, attaining high electrical conductivity, biocompatibility, mechanical robustness, and tissue adhesion without sacrificing other physicochemical qualities remains challenging. These materials require a combination of physicochemical, biological, and mechanical attributes [15]. 3D printing is increasing in popularity in regenerative medicine and tissue engineering due to its capacity to manufacture complex structures with variable mechanical characteristics, degradation rates, and cytocompatibility. However, the absence of bio-inks with these qualities remains an obstacle. SF, on the other hand, has great characteristics and diversity in ink [16]. The 3D bio-printing sector is making great progress, but generating critical-sized synthetic tissue structures remains a long-term aim. Silk fibroin, a natural substance with distinct structural properties, is a potential bio-ink material. Researchers used reverse engineering to enhance shear thinning behavior, printability, cytocompatible gelation, and structural fidelity in 3D bio-printing, focusing on key sources of SF [17]. 3D printing technologies allow for the construction of complicated tissue engineering scaffolds, a significant technological achievement in the tailored biomedical area. Bio-ink, a combination of materials and biological molecules, is used in bio-printing to mimic the extracellular matrix present in live organisms. Due to its exceptional features and versatility, SF may be employed to create complicated structures with variable mechanical properties, degradation rates, and cytocompatibility, making it a significant tool in the clinical setting [18].

3. Recommendations

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

- Nanotechnology-enabled SF composite films have exceptional antibacterial activity, mechanical characteristics, non-cytotoxicity, cell adhesion, and water and vapor permeability, making them viable wound dressing materials.
- Bio-inspired Science Fiction Biomaterials have the potential to revolutionize material manufacturing by boosting sustainability and environmental friendliness. This might lead to high-performance deliverables that have an impact on both the scientific community and society, possibly influencing future material processing.
- Standardizations are required of modifications in fibroin microstructure over time, yet tunability may not be feasible due to lengthy manufacturing and utilization durations. Chemically cross-linked fibroin is less affected by external circumstances, but further research is needed to maintain the same biological performance as unmodified protein. Tunability may not apply to chemically cross-linked fibroin.
- Integrating diverse strategies for creating synergistic bactericidal action in SFBs is an effective strategy. However, most approaches lack sufficient characterization information and are not yet suitable for clinical use. Future research should concentrate on in vivo investigations, consistent verification test methods, and an understanding of each approach's bactericidal processes in order to improve clinical translation.
- The area of multiscale modeling of natural silks and silk-based biomaterials continues to evolve, offering challenges and opportunities. Effective molecular-to-fiber modeling can help us better understand natural silk fibers while creating beneficial biomaterials.
- SF's exceptional features, including as biocompatibility, tunable biodegradability, water solubility, excellent optical transmittance, mechanical robustness, lightweight, and simplicity of production, make it outstanding for next-generation biocompatible adaptable electronic devices.
- SF is frequently employed as substrates, encapsulating materials, and scaffolds in flexible wearable and implantable electronic devices including electronic skins, bio-absorbable electronics, and therapeutic electronics due to its desirable biological attributes.
- When coupled with 2D nanomaterials, SF has the potential for enhancing bone, cartilage, ligament, and tendon tissue engineering. It has shown promise in lowering the likelihood of scar tissue formation in skin and wounds. However, therapeutic applications are limited, necessitating additional studies for FDA-approved products produced from this biomaterial.

Conclusion

Silk-based materials are transforming several sectors due to its strength, mechanical characteristics, biocompatibility, processing, and modifiability. Bio-inspired indirect building methodologies offer great processing ability and modifiability, satisfying a wide range of biological requirements. This paper discusses common silk building components, with an emphasis on extraction techniques and design strategies for functional RSF biomaterials. Recent breakthroughs in cell material interactions, soft tissue regeneration, and flexible bio-electronic devices emphasize the significance of these methodologies in creating and changing functional RSF biomaterials, hence boosting the high-quality use of natural silk or other biomass materials. SF has enormous potential in a variety of biological applications, including wound healing. Sponge, hydrogels, nano-fibrous matrices, scaffolds, and composite films are examples of recent breakthroughs in SF-based material development. Sponges have a larger porosity, stronger mechanical strength, and faster epithelial cell and collagen deposition. Hydrogels keep burn dressings wet. Nano-fibrous matrix and scaffolds enhance porosity, oxygen permeability, and mechanical characteristics. Electro-spinning is a sophisticated method for creating nano-fibrous mats and scaffolds. SF micro-particles and nano-NPs exhibit distinguishing characteristics such as subcellular size, stability, high carrier capacity, and improved collagen fiber cell development. SF, a natural polymer, is widely employed in biomedical applications because to its superior biocompatibility, outstanding mechanical qualities, regulated biodegradation, and adaptability. Despite its lack of natural antibacterial activity, attempts have been undertaken to improve its antibacterial capabilities. The water-based processing of SF, as well as the existence of numerous functional groups, have allowed SFBs to be functionalized with a variety of antibacterial agents. Furthermore, SF's electron-donating capacity has made it an effective reducing and stabilizing agent for green production of bactericidal nanoparticles, making it easier to create antibacterial SF-based nano-composites. However, bacterial resistance, limited stability, high cost, and possibly cytotoxic consequences remain significant constraints. SF, a well investigated substance in a variety of tissue engineering domains, requires more study to bridge the gap between academic and clinical investigations. This entails extensive standards and regulatory clearances. Researchers should not be discouraged from pursuing pre-market approval, which may have harder standards and a lengthier procedure, but also provides greater confidence in the created medical device.

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