Silk Materials Light Up the Green Society

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1. Introduction

Growing policies embracing green and renewable energy greatly spur the technological innovations and developments of new energy sources, environmentally-friendly materials, and carbon-saving techniques. Aiming for replacing the polluional and nondegradable petroleum-produced plastics, emerging classes of natural materials offer unique capabilities for reusable/recyclable energy-related usage and (bio-)degradable/compostable disposition. Silk proteins, including natural silk fibroin, spider silk, and artificial synthesized recombinant silk counterparts, serve as options for founding a range of powerful devices and systems that harvest and storage energy for mainly human-centered biomedical applications, in an eco-friendly and biocompatible fashion (Figure 1). Silk-based bioelectronics, biophotonics, and optoelectronics supported by advanced manufacturing technologies will make the best of silk’s favorable properties and promote high-tech, medicinal, and green social growth which, in consequence, can improve environmental conservation at individual, community, and global levels.

2. The Landscape of Silk-Based Energy Device

Within the green energy field, silk composites with novel electronic, structural, and biological properties are highly desirable. Natural silks spun by spiders and silkworms represent the strongest and toughest natural fibers known and offer intriguing opportunities for serving as biocompatible device framework. Moreover, the abundant nature of amino acids and hydrogen bonding within silk matrix endorse the compelling electrical properties. In parallel, genetically engineered silk proteins preserve the intrinsic features while acquiring new customizable capabilities by rearranging and repeating certain gene sequences. Recent progresses in green energy have highly exploited the capabilities of silk to provide system with unprecedented (bio-)functionalities. For example, groundbreaking proof-of-concept works in energy-harvesting devices 6 years ago triggered exciting opportunities. In 2015, Zhang et al. and Kim et al. separately reported implantable and fully biodegradable TENGs based on silk fibroin to enable in vivo energy harvesting with high-performance physiological monitoring and therapeutic functionalities for epilepsy.\[^{[1,2]}\]

The revolutionary and pioneering advancements of silk materials in recent years have provided numerous opportunities for the great trend of sustainable green energy. Working as an eco-friendly replacement for conventional energy harvester or storage device, silk-based energy sources that get intensive attention are regarded as new solutions in flexible human-integrated applications. Compared with other synthetic polymers, silk materials present outstanding biocompatibility, biodegradability, and many other attractive properties owing to the natural protein composition, various modification methods, large-scale green production, and superior fabrication techniques. Herein, recent progress and ongoing challenges posed by the utilization and translation of silk materials in green energy application are discussed.\[^{[3,4]}\]
Since 2016, different silk-based materials and technologies have been explored for green energy harvesting; yet one general consensus suggests that the next technological breakthroughs will be enabled via exceeding the intrinsic electrical properties of silk materials and exploring/integrating various kinds of nanogenerators. Biotechnology combined with multiscale manufacturing offers several advantages. For instance, the customizable triboelectric property (charge affinity) of spider silk introduced by genetic engineering breaks through the limitation of natural material, therefore realizing unmatched energy output compared with other biomaterials.\textsuperscript{[5]} The multiscale manufacturing techniques of the silk (mostly converted from semiconductor field) permit large-scale fabrication and integration with numerous today’s state-of-the-art energy harvesting devices.\textsuperscript{[6]} In addition, these green technologic frameworks offer well-established quality control procedures that can reduce the economic cost and keep the eco-friendly purpose.

Applications driven by silk materials and advanced manufacturing are increasingly abundant (Table 1). Some directly resemble silk-based TENG with piezoelectric nanogenerator, while others optimize the design of hybrid silk-based nanogenerator to maximize the nonlinear superposed output.\textsuperscript{[7,8]} Thermoelectric generator made by silk fabric allows wearable thermal energy harvesting and enriches following self-powered textiles.\textsuperscript{[9]} Nanofluidic device prepared with ultrathin nanoporous silk membrane utilizes the outstanding chemical and mechanical properties of silk protein to conduct osmotic energy harvesting.\textsuperscript{[10,11]} Silk-based supercapacitor shows high capacitance and stability, which can be designed to be tunably transient and provide viable alternatives for powering flexible and implantable bioelectronics.\textsuperscript{[12]} Prototypes of silk-based primary and secondary batteries are also developed by capitalizing the abundant functional groups in the silk, offering a new perspective for the application of biomass materials in advanced batteries.\textsuperscript{[13,14]} In general, silk materials play a key role in these energy harvesting and storage devices in ways that integrate inorganic and organic components for new properties and functions, exhibiting potential for complementing energy source in wearable and implantable devices.

![Image](https://example.com/image.png)

**Figure 1.** Silk materials, including silk fibroin, spider silk, and genetically engineered recombinant silk protein, bring new opportunities for green energy applications.

| Category | Application | Silk-specific advantages | Challenges |
|----------|-------------|--------------------------|------------|
| Triboelectric and hybrid nanogenerators\textsuperscript{[1–5,7,8]} | Human-integrated electronics | Mechanically stable | Lack of uniform evaluation criteria |
| | | | |
| | Implantable energy source | Abundant negative charges | Complicated for practical usage |
| | | Abundant functional groups | |
| | Wearable self-powered sensor | | |
| | - Electronic textile | Genetically customizable | |
| | Medical treatment | Biocompatible and biodegradable | |
| | Antibacterial electroporation | Potential for large-scale fabrication | |
| Thermoelectric generator\textsuperscript{[9]} | Wearable energy harvester | Mechanically stable | Mediocre performance |
| | | Flexible substrate | Limited practical usage |
| Osmotic energy harvester\textsuperscript{[15,11]} | Ocean energy harvester | Mechanically stable | Need to improve long-term stability |
| | Water purification | Natural narrow nanochannels | Nongreen processing |
| | Desalination | Abundant negative charges | Limited upscaling variety |
| Supercapacitor\textsuperscript{[12]} | Implantable energy storage | Biocompatible and biodegradable | Complicated for practical fabrication |
| | | Versatile fabrication | Mediocre performance |
| | | Robust dielectric constant | |
| | | Need bioincompatible accessories (supporter, wire and connector) | |
| Primary and secondary battery\textsuperscript{[13,14]} | Biodegradable battery | Biocompatible and biodegradable | |
| | | Abundant functional groups | |
| | High-performance anode | Enhanced ionic transport | |
| | Advanced lithium metal battery | Mechanically stable | |
| | | | |

**Table 1.** Summary of silk-based green energy devices.
3. Challenges Associated with Silk Materials

While decent progress has been made on introducing silk with green energy topics, the in-depth translation of silk-based energy system from academic laboratories to commercial companies remains a challenge. In today’s research landscape, there is a trade-off between functionality and performance: sustainable, natural material–based prototypes are typically built to highlight selected key functions, whereas practical applications have critical performance specifications for the entire scope. Challenges include scaling, hermetic encapsulation, wireless communication, system-level integration, versatility for specific needs, uniformed evaluation criteria, abundant material supply, and compliance to handling in a practical use scenario. Research efforts are still needed to assess their translational potential, and define a sound way forward to practical usage. Apart from these, some of the silk processing approaches, involving formic acid, hexafluoroisopropanol, and other organic solvents, are not environmental friendly for which there is currently a lack of alternative paths. Table 1 identifies and summarizes current major categories associated with advantages and critical challenges of silk-based green energy devices, which once tackled will help to convert technological proof-of-concept into the nonlaboratory trial.

Another current bottleneck for the successful translation is the need for pushing silk to meet the validation protocols and regulatory norms in the clinical practice. Only several silk formats, mainly pure silk fibroin composite, have been approved by the food and drug administration from country to country. As the major applicable direction of silk-based energy device is for human body, extensive tests and important validation milestones must be demonstrated, from an industrial perspective, before incentivizing enough attentions and applying for practical trials.

4. The Road Ahead

Although the translational road of silk-based energy device is arduous and costly, both scientists and investigators should be encouraged to push their laboratory research and multidisciplinary collaboration toward practical adoption. Many countries around the world have introduced policies to motivate their societies to confront and conquer growing carbon emission challenges. Take China as an example: the relationship between green energy and sustainable social growth matters greatly in China; from the 13th Five Year Plan (2015–2020) to the upcoming 14th Five Year Plan (2021–2025), China’s great and continuing transition to a green economy has immense implications for sustainable development both domestically and worldwide. Silk material, as one type of green natural resource, has advanced rapidly to the point that silk can be expected as standard building blocks for future sustainable applications. The new high-tech version of “silk road,” broadened by silk-based energy technology, will continue and light up the bright upcoming green society.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

bioelectronics, energy harvesting and storage, green energy, silk materials
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