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The Properties and Application of Natural Spider Silk: a Literature Review

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Abstract: *Drag silk, which is produced by the main ampullate silk gland, is a kind of natural insect silk which outperforms some other kinds of silk. Given its exceptional mechanical characteristics and excellent biocompatibility, drag silk, a kind of spider silk, does have the potential to be utilized by humans. The excellent properties of natural spider silk make it useful in many fields. But due to the cannibalistic nature of spiders, spiders cannot be reared on a large scale to meet the huge demand for spider silk. The development of recombinant spider silk protein and artificial spider silk through research and development is vital for the commercialization of spider silk and its applications. This research outlines the possible applications of natural spider silk by examining its physical, biological, and characteristic features. Due to its extraordinary physical and biological properties, drag silk and its corresponding silk proteins have been found to have the potential for the applications in the aerospace industry and biomedical treatments.*

Keywords: *Spider silk, applications, characteristics, mechanical properties, biocompatibility*

1. Introduction

Webbing spiders have at least six different glands that can be found on their bodies. These spiders have a wide variety of silk glands, which allow them to produce a wide variety of spider silks. These spider silks are ultimately extracted from the silk wart. In order to manufacture a sufficient quantity of spider webs that conform to the numerous distinct physical property specifications, a large number of different types of spider webs are manufactured. The extraction of major ampullate silk, which is produced by the major ampullate gland, is the responsibility of the anterior filament warts of the major ampullate gland. Its most common use is in spider webs, specifically as drag silk, radius silk, and frame silk. Other names for these types of silk include: Spiders can pull drag silk at any time of the day or night. Some types of silk have a degree of elasticity that is practically identical to that of rubber, while the tensile strength of silk fibres is comparable to that of steel. Silks have a level of toughness that is two to three times greater than that of synthetic fibres such as nylon or kevlar, and this is due to the fact that both of these properties are present in silk. In addition to all of these benefits, spider silk is non-allergenic, completely biodegradable, and antimicrobial. Specifically, drag silk is comparable to the very best synthetic fibres that can be purchased at the present time. Because of the exceptional mechanical properties, it possesses as well as the fact that it is biocompatible, researchers from all over the world are very interested in it. Humans have known about the amazing qualities of natural spider silk for a very long time. These qualities have been thoroughly documented. In point of fact, the spider silk was utilised by the ancient Romans and Greeks for the weaving of garments, the construction of webs, and the binding of wounds. The indigenous people of Australia made use of spider silk and even rubbed the bodies of crushed spiders into the netting of their nets in order to attract fish. This was done so that they could catch more fish. Before the beginning of World War II, the sights of many rifles and other types of weapons were constructed out of spider silk. This was a common practise. People have discovered an increasing number of applications for natural spider silk as human knowledge and capabilities in the fields of science and technology have improved over time. Even though it would be perfectly rational to raise natural spiders in order to generate the fibres that are in demand, doing so would be extremely time-consuming and expensive due to the numerous processes that would need to be performed in order to accomplish this goal. Additionally, it has not been demonstrated that the methods or processes for harvesting spiders on an industrial scale are successful. Despite the fact that such methods and processes already exist, this is something that has not been shown. Scientists combine the fundamental principles and structure of natural spider silk with either the technology of biological gene recombination or the

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technology of chemical synthesis in order to create artificial spider silk. This allows the scientists to recreate the natural properties of spider silk. Researchers have been able to conduct in-depth studies of the components, structure, and properties of spider silk as a result of major innovations in genetically modified genes, polymers, and nanotechnology. These advancements have made it possible for researchers to study spider silk in greater detail. This paper provides a summary of some of the challenges that are currently being faced following a review of recent research and applications of natural spider silk and its biomimetic structural materials in a variety of different fields from the perspectives of superior mechanical properties and biocompatibility. The review began with an examination of recent research and applications of natural spider silk and its biomimetic structural materials. This is done in consideration of the myriad of different qualities that natural spider silk possesses.

2. Varieties and properties of natural spider silk

Spiders found in nature are capable of producing a wide variety of spider silks with varying qualities throughout their entire life cycle. This is either because they are forced to produce spider silk in order to survive or because they do so for other reasons. There is a large degree of variation in the quality of spider silk produced by various species of spiders. This variation is caused by the fact that different species of spiders have varying numbers of glands that produce silk. Six or seven distinct types of silk glands have been identified in the vast majority of the spiders that have been investigated up until this point. (Shown in Figure.1 below) As a direct consequence of this, it is possible to manufacture anywhere from five to seven different varieties of spider silk. These spider silks are typically arranged into several categories and given names in accordance with the purposes that they fulfil. The Major Ampullate silk gland is responsible for producing dragline silk, which is distinguished by a high level of both strength and pliability. This type of silk is known as "dragline silk." In the process of building the spider web, it is utilised in the construction process as the escape rope, the radius silk, and the frame. It is the primary component that constitutes the web for catching animals. It is the type of silk that, in comparison to the other six types, possesses the greatest amount of tensile strength. The minor ampullate silk is used in the construction of the central helical structure of the spider web, which serves to maintain the web's integrity. This structure is located in the middle of the web. Flabelliform silk has a high degree of ductility, and aggregated flabelliform silk can be attached to the surface of flagellate threads to increase their viscosity. The aciniform silk is the most durable type of spider silk and possesses outstanding characteristics in terms of its physical makeup, including high levels of both strength and elasticity. Aciniform silk is produced by the aciniform spider. [1]

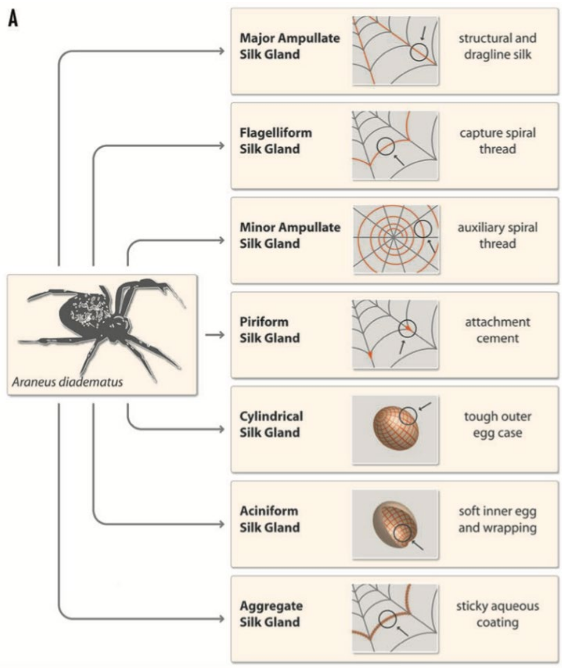

Figure 1: Summarization of structures of several diverse types of spider silk produced by female orb-weaving spiders such as the European garden spider, Araneus [2]

The spider silks that were described above each serve a different purpose, and as a result, each type

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of spider silk possesses its own distinct set of mechanical properties. According to the strain curve, dragline silk possesses high levels of strength, modulus, and toughness in addition to high levels of breaking strength [3], which makes it widely studied by scientists today. When compared to the silk produced by a variety of other animals, as well as the vast majority of synthetic fibres developed by humans, spider silk possesses superior mechanical properties. Table 1, which can be seen over here, is an outline of the mechanical qualities that spider silk possesses. The data that is provided in the following paragraphs reveals that the elongation of spider silk is superior to that of both steel and aramid fibres. Because of this, spider silk has an advantage over both silk and nylon in terms of its ability to lengthen. The exceptional quality of spider silk is partially due to the fact that the elongation upon break can reach lengths that are two or even four times their original length. In light of this fact, spider webs can be differentiated from other kinds of materials in terms of their elasticity. Natural spider silk is a promising material with a wide range of applications because it possesses a tensile strength that is approximately five times that of steel, is comparable to Kevlar, is significantly superior to silk, rubber, and nylon, and is about as strong as spider silk. In addition, natural spider silk is about as strong as spider silk. In addition, the strength of natural spider silk is comparable to that of synthetic spider silk. Spider webs, which are made out of spider silk and possess a significant amount of breaking energy, have more strong physical properties than other materials. This is due to the fact that spider webs have been formed out of spider silk. [4]

Table 1: Comparison of the mechanical properties of spider silk and other four materials from three aspects

Material	Elongation at break (%)	Tensile Strength(N/m^2)	Breaking energy(J/kg)
Spider silk	35-50	5×10^9	1×10^5
Nylon	18-26	5×10^8	8×10^4
Kevlar	2-5	4×10^9	3×10^4
Silkworm silk	15-35	6×10^8	7×10^4
Steel	8.0	1×10^9	5×10^3

Spider silk demonstrates a greater level of mechanical performance when compared to other natural fibres and even some synthetic threads. This is owing to its well-balanced combination of strength and elasticity, (According to Table 1 and Table 2) which sets it apart from its competitors. Because of this, it is able to outperform both types of fibres in particular situations.[2]

There is a clear distinction between the silk produced by insects and that produced by spiders on every level, from the molecular level all the way up to the structural arrangement of the proteins and the mechanical qualities of the thread. On a molecular level, insect silk is made up of a significant quantity of sericin proteins, but spider silk does not contain any of these components. In contrast to the spidroins found in spider silk, the proteins that are responsible for the fibrillar structure of insect silk (also known as fibroins) are made up of light-chain and heavy-chain counterparts. When compared to MA silk, like as that produced by spiders, silk produced by silkworms is significantly less durable and less capable of stretching. Silk produced by silkworms can either be rigid or elastic, depending on the conditions under which it is spun, whereas the silk produced by spiders combines these two qualities. [5]

Although the conditions of spinning have a substantial impact on the mechanical properties of both types of silk, the proteins involved are mostly responsible for the genuine distinction that exists. As a consequence of this, researchers have spent a lot of time looking for ways to recombinantly generate and manipulate the natural proteins that makeup spider silk.

Table 2: Mechanical properties of natural and synthetic fibres

Material	Density(g/cm^3)	Elasticity (%)	Toughness(MJ/m^3)
Major Ampullate silk	1.3	27	180
Flag silk	1.3	270	150
Silkworm silk	1.3	18	70
Nylon 6.6	1.1	18	80
Kevlar 49	1.4	2.7	50
Carbon fibre	1.8	1.3	25
Steel	7.8	0.8	6

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3. Application of spider silk material

3.1 Applications based on Physical properties of spider silk（Aerospace applications）

Because of its low weight and high strength, natural spider silk is frequently used in the aerospace sector. This is due to the fact that natural spider silk is quite strong. In the study that Mayank and his colleagues carried out. [6] In the course of this experiment, structural models of aeroplane windowpanes were investigated in order to determine how they stacked up against industry standards. Epoxy resin was used as the matrix material, and spider silk fibres were utilised as the reinforcement for the material. Both of these aspects were considered for inclusion in the experiment. After construction of the model, it was discovered that the use of the new material results in a reduction in the amount of stress that is created in the model. The construction of the model and the identification of the points of greatest tension allowed for the successful completion of this task. The fact that this is the case contributes to the new material's outstanding resistance to pressure. Because it is different from acrylic, which is the material that is typically used, this new material, which is a composite of epoxy and spider silk, will be a better material for the windowpanes of aeroplanes because it is thinner while still being able to take the same load, which will result in a reduction in the amount of weight that is carried by the aircraft. In order to arrive at this conclusion, the data, which included weight reduction, safety factor, and the weight of material contained within each model, were analysed and then calculated.

3.2 Medical applications based on the biocompatibility of spider silk

3.2.1 Spider silk coating on silicone implants

Taking into consideration the fact that natural silk is biocompatible in both vitro and in vivo (cytocompatibility, low immunogenicity, biodegradability, low toxicity). [7] Because the cytocompatibility of recombinant spider silk protein is comparable to that of natural silk, it is appropriate for use in biomedical applications. [8] [9] Philip et al. [10] used recombinant spider silk protein eADF4(C16) (a protein in the silk of the European garden spider Araneus diadematus) [11]. In the experiment, Sprague-Dawley rats served as the subjects, and a silicone prosthesis that had been covered in spider silk was affixed to each animal. Both treatments were administered to the rats, and then the outcomes were analysed. Based on the results of the experiments, it was determined that spider silk, which was the component of the bio coating that was utilised, was well tolerated. There was no evidence of infection or ectopic inflammation, and the healing process of the wounds, liver granulomas, or lymph node modifications were not impaired in any way that was detected. The recombinant spider silk protein eADF4(C16) successfully coats the surface of medical-grade silicone implants during the first few months after insertion. This procedure takes place over the course of a number of consecutive months. Because of this, there has been a clear improvement in the biocompatibility of the implant biophase. This shift is a direct result of the aforementioned event that took place. To summarize, the newly discovered covering made of spider silk has a tremendous potential to significantly improve the medical performance of existing silicone implants while only requiring a minimal amount of additional effort on the part of the medical professionals. This is all possible with only a small amount of extra work being required from them.

3.2.2 Drug delivery

Due to the biocompatibility of natural spider silk, silk protein-based materials are promising materials for the delivery of drugs and other active ingredients. Thus according to Andreas Lammel et al. [12], while eADF-4(C16) is negatively charged at pH 7, complexes can be created with positively charged molecules by electrostatic interactions. When drug molecules are pulled to the filament by electrostatic forces, the researchers found that eADF-4 (C16) particles can be created and loaded in this system's all-water method under normal conditions. This was a breakthrough finding. Given that the product is biocompatible and can encapsulate volatile substances, this is a significant advantage that should not be overlooked. Spider proteins have features that make them appealing to anchorage-dependent cells. These qualities include alternate regions of hydrophilicity and hydrophobicity, as well as charged residues. These characteristics increase protein adsorption and cell adhesion. [13] In the model experiment, John G. Hardy et al. [14] added a cationic drug into the film composed of eADF-4(C16) and measured the release of the model drug within one month. In the films that contained a greater amount of eADF-4, the drug was released in a pretty speedy way and in a significant amount of volume when the films were incubated with elastase and trypsin (C16). Because of the way the movie is shaping up, there is a chance that the release date will be shifted around to accommodate the change. According to the findings of the research, this silk-based composite has the potential to be utilised as a tissue scaffold or an implantable drug delivery system for cationic antipyretic drugs such as haloperidol for up to a number of weeks at a time. In addition to this, it is capable of performing the function of a biocompatible and biodegradable coating for implants that are either bioresorbable or biodegradable. One possible application for the chemical is outlined here.

4. Conclusions and future perspective

In general, the human race has reaped many benefits from and discovered a wide variety of applications for animal silks such as spider silk. As a result of the natural spider silk's extensive list of desirable qualities and the spidroin proteins that compose it, scientists conduct research, develop new technologies, and work toward the goal of improving the material's characteristics. Although the mechanical and physical properties of man-made fibres cannot be matched to those of spider silk, humans have gradually learned about the potential uses of recombinant spider silk fibres in the military, sports equipment, aerospace, and other industries. This is the case despite the fact that spider silk cannot be replicated by man. Taking advantage of the fact that recombinant spider silk protein eADF4 (C16) is biocompatible, extensive research is also being conducted on its potential applications in the fields of medicine and cell biology. Even though natural spider silk has substantial value for research and applications due to the fact that it is mechanically strong and biocompatible, it is not possible for natural spider silk alone to satisfy the need for spider silk. The investigation of synthetic spider silk is laden with a number of significant difficulties that must be overcome. However, natural spider silk has the advantage of having a multi-level structure, which is beneficial in the processes of silk manufacturing, spinning, and other operations. Chemical synthesis has the benefit of having simple stages and a low cost. Although the mechanical qualities of artificial spider silk threads created by recombinant spider silk proteins cannot match those of genuine spider silk, their mechanical properties can match those of native spider silk. The challenge of filling the post is still difficult and needs to be resolved as soon as humanly possible. [15] Analyzing the structure-function relationship of spider silk proteins in the near future will not only reveal the "secrets" behind the extreme toughness of silk threads, but it will also help to engineer and design novel polymeric materials that are inspired by nature. This is because the "secrets" behind the extreme toughness of silk threads are the relationship between the structure of the protein and its function. Scientists will be able to produce tailor-made spider silk materials with exceptional qualities whose diversity cannot be obtained by using conventional materials once they have direct control over the construction of silk. The mysterious cloak that has been cast over spider silk is gradually being lifted as a result of ongoing research into the subject, and at the same time, work is also continuing to be done on the production of artificial spider silk on a massive scale. In other words, the veil that has been cast over spider silk is gradually being lifted. The military, medical, aerospace, construction, and automotive industries will all significantly benefit from the improved properties of spider silk bionic materials, which will eventually displace traditional materials in a variety of different ways. This will be the case in a number of different ways. In spite of the fact that numerous promising applications of spider silk have been proposed based on the extraordinary properties of natural spider silk, such as applications in the military field, the material field, the medical field, the textile field, and the field of environmental protection, only a small number of these applications have been tested and carried out by scientists from both the United States and other countries. It is possible that this is due to the lack of spider silk fibres as well as the protein found in spider silk.

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