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Processing, Structure and Properties Analysis of Spider Silk Fiber For Textile Biomedical Engineering Application

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ABSTRACT

Spider silk fiber (SSF) is a kind of natural biomaterial with superior performance. Its biocompatibility and mechanical properties are incomparable with those of other natural and artificial materials. The natural spinning process, chemical composition, structure and properties of spider silk had remained mystery for a long time. More than half a century, people had an understanding of the application of spider fiber. The ancient Greeks used spider silk fiber used as medical textile to stop bleeding and heal wounds. Purposes of this research work were focused and systematic attempts made in the biological aspects, properties and structure of the spider silk fibers were studied for easily spin ability and weave ability performance for biomedicine application, especially biocompatible sutures and diminishing micro-organism growths. The experimental results confirmed that, the specific toughness of spider silk fiber was comparable to some of the best synthetic materials which are commercially used. The test result revealed, that the breaking stress of the spider silk fiber for ten samples of spiders range from 1184 to 1452 N/mm2 with elongation at break ranging from 12 to 27 %. While, the breaking stress of Kevlar 49, Carbon fibers and high tenacity nylon are recorded 2000, 1750 and 1600 N/mm2, with the elongation at break of 4.0%, 1.0% and 16% respectively. Generally, its biocompatibility and their mechanical properties were becoming more preferable medical textile materials for biomedical engineering research areas.

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1. Introduction

Biomaterials, having evolved over millions of years, often surpass man-made materials in their properties. Researchers continually seek to develop new materials that are stronger, lighter, or tougher than those currently in use. Spider silk is an outstanding natural fibrous biomaterial that consists almost entirely of large proteins. It is an extremely strong material and, on a weight basis, is stronger than steel. Natural spider silk fiber is a type of protein fiber secreted by spiders through their silk glands. It belongs to the class of bio-elastic protein-based fibers [1]. Generally, spider silk is a highly ordered protein fiber spun by spiders. An in-depth understanding of its natural structuring and synthesis highlights the importance of hierarchical structures in terms of real-world functionality [2,3]. Spider silk is one of the most sought-after biomaterials. Also known as “gossamer,” this protein fiber is both flexible and lightweight. Due to its high demand and limited availability, spider silk has even acquired the nickname “Holy Grail.” For a spider, this fiber is used for multiple purposes: catching prey, serving as a lifeline while jumping, and creating egg sacs [4]. Natural spider silk is favored by researchers primarily for its outstanding mechanical strength, temperature adaptability, and unique composition. The fiber exhibits high specific strength, excellent elasticity, and remarkable toughness, surpassing that of other natural and synthetic fibers. Spiders use silk for constructing webs, producing egg sacs, wrapping prey, creating lifelines for jumping or escaping, transferring semen from the abdomen to the male palp, marking draglines with pheromones, and as a retreat shelter [5]. Historically, early Romans and Greeks used spider silk to weave fabrics and nets and even to bandage wounds. Australian Aborigines used it for fishing lines and nets, sometimes rubbing crushed spiders on nets to attract fish. Until World War II, the crosshairs on many weapons were made from spider silk. The first large-scale weaving with spider silk was carried out in the late 1800s by a French Jesuit priest, Jacob Paul Camboué [6,7]. Currently, over 34,000 spider species are known, and roughly 50% use webs to catch prey. Moreover, more than 130 different shapes of spider webs have been documented. Among the most studied are orb webs, which consist of several different types of silk, as observed in the European garden spider Araneus diadematus [8-10]. Natural spider silk is similar to silks produced by other organisms but performs slightly better in all aspects. It primarily consists of proteins rich in nonpolar and hydrophobic amino acids, such as glycine and alanine, while containing little or no tryptophan. Compared to common cellular enzymes, silk proteins exhibit an unusual amino acid composition.

Spiders (Araneae) rely on silk throughout their lifetime and are unparalleled in the diversity of silks they can synthesize. A single orb-web weaving spider (Orbiculariae) possesses seven types of specialized abdominal silk glands. Each gland type produces a different silk fiber or glue, each with a unique function. The diversity of silk function is matched by the diversity of silk mechanical properties. Spider silk fibers exhibit impressive mechanical properties and are primarily composed of highly repetitive structural proteins, termed spidroins, which are encoded by a single gene family. Most characterized spidroin genes remain incompletely understood due to their extreme size (typically >9 kb) and repetitiveness, which limits comprehension of the evolutionary processes that produced their unusual gene architectures. For example, major ampullate glands produce dragline silk; tubuliform glands synthesize large-diameter egg-case silk fibers; capture spiral threads of the orb-web originate in the flagelliform glands; and prey-wrapping silk is synthesized in aciniform glands, as shown in Figure 1 [11-14]. After secretion from the silk glands, silk proteins exist in an aqueous solution and lack significant secondary or tertiary structure. Particularly in their repetitive core domains, however, the long sequences permit weak but numerous intra- and intermolecular interactions between neighboring domains and proteins as they pass through the spinning duct. These substructures are thought to be responsible for the mechanical strength of the silk thread. The elasticity of silk arises from regions with low electron densities, which are characterized by amorphous structures with few defined elements of secondary or super-secondary structure. This arrangement closely resembles that of protein hydrogels. Upon tensile loading, the hydrogel-like areas can partially deform, contributing to the elasticity and flexibility of the thread [15-17].

In this research, the structure, physical, and mechanical properties of natural spider silk fibers were systematically investigated to evaluate their suitability for medical textile applications. The study aims to understand how the hierarchical structure of the silk contributes to its remarkable strength, elasticity, and toughness. By characterizing these properties, the work seeks to identify potential advantages of spider silk over conventional synthetic and natural fibers used in medical textiles. Ultimately, this research intends to provide insights that could guide the development of biocompatible, high-performance materials for applications such as wound dressings, sutures, and other biomedical devices.

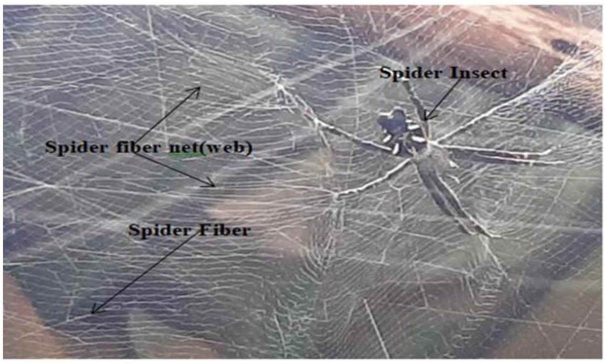

Figure 1. Appearance of Natural spider Silk webs

2. Materials and Methods

2.1. Materials

According to Bird Watching HQ, 2023 report, the 11 common spiders that live in Ethiopia are Hairy Golden Orb-weaving Spider, Adanson's House Jumper, Shorthorn Kitespider, Southern Baboon Spiders, Bark Spiders, Pantropical Jumping Spider, Camel Spiders, Crab Spiders, Wolf Spiders, Cellar Spiders and Harvestmen. From these various types of spider Bark Spiders were used this experimental study.

Spiders Silk Fiber (SSF): Bark Spiders were used this study and a genus of 18 species that range over the African continent are found. The silk that Bark Spiders produce is the toughest biological material humans have ever studied, twice as strong as any other spider silk known to science. And not only do Bark Spiders have the strongest silk, but they also build the largest webs. This impressive species holds the record with a surface area of up to 2.8 square meters (30 sq ft) (Bird Watching HQ, 2023). The spider silk fibers were carefully collected from the bark of the tree in the forest and conditioned for 24 Hr in lab as shown in Figure 2.

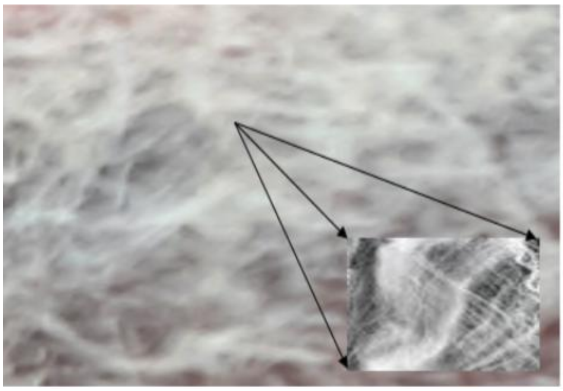

Figure 2. Spider Silk Fiber (SSF)

2.2. Method

Morphological Structure: The morphological analysis of spider silk fiber structures were analyzed by using optical microscopic and EVO-40 Scanning Electron Microscope after the fiber was coated with gold for 60sec.

Linear Density: The linear densities of the fibers are expressed by measuring the length of a known mass of the fiber in indirect system i.e. length/mass or by measuring the mass of a known length of the fiber in direct system i.e. mass/length.

FTIR Analysis: BRUKER-37 FTIR was used for the characterization spider silk fibers with the measurement of the spectral range from 400–4000 cm^{-1}.

Mechanical Property: SHIMADZU strength tester (with strain rate of 100 % per minute) was used for analysis the tensile strength and elongation of spider silk fibers having a gage length of 1.25 cm effective length of 10 samples as per the ES ISO 5079 standard.

3. Results and Discussion

Spider silk is a kind of natural biomaterial with superior performance. Spider silk is incredibly tough and is stronger by weight than steel of the same diameter. Its mechanical properties and biocompatibility are incomparable with those of other natural and artificial materials

3.1. Properties and Structure of Spider Silk Fiber

Like other protein base natural fibers, the major building blocks of the spider silk fiber biopolymer are amino acids. It is principally important to highlight the key differences in silkworm and spider silk performance to justify the distinction rationale. SSF shows different biological characters and physical properties due to its different feeding style, hierarchical structures of amino acids, spinning conditions and spider species.In general, the mechanical properties of spider silk have strength advantage over silk over silkworm. This was due to the specific composition of amino acid sequences in the spider silk and that form highly repetitive domains of both spidroin which is the main protein of spider silk while fibroin which is the main protein of silkworm silk fiber. One of the outstanding characteristics of spider silk is its fineness as shown in Table 1. This was idea was confirmed by Pérez-Rigueiro et al., 2000; Andersson et al., 2016 doing research work on spider silk fibers. Many researcher works have been worked out and proposed different structural models to describe the packing of molecular chains of spider silk fiber in unit cells having large enough to accommodate the amino acid residues with simple side chains such as serine, glycine and alanine. Spider silk has good temperature characteristics. The spider silk still has good stability at 200°C, and its structure will be destroyed when the temperature goes beyond 300 °C.

Table 1. Difference between Spider Silk and Silkworm Fiber.

Property	Spider Silk fiber (SS)	Silkworm fiber
Strength-to-density ratio	high	Lower than SS (Aleksandra P. et al, 2020)
Mechanical properties	moderate	Weaker strength than SS (Shaoand Vollrath, 2002) (Andersson et al., 2016).
Impact energy Absorption	high	Lower than SS (Du et al., 2011), (Aleksandra P. et al, 2020)
Linear Density(Tex)	0.013	0.117 Frank K. Ko, et al,2006)
Diameter mean value (μm)	3.4	12.9 (Frank K. Ko, et al, 2006)

3.2. Chemical Composition and FTIR Analysis of Spider Silk Fiber

There are four main parts of a spider web; the hub or center of a web where the spider usually rests, the frame threads or borders of the web, the sticky spiral or insect catching area, and the anchor points like the guideline attaching the web to the substrate. Spider silk primarily consists of proteins that possess large quantities of nonpolar and hydrophobic amino acids like glycine or alanine, but for example, no or only very little tryptophan. The research work revealed that, the exact composition of these proteins depends on factors including species and diet. Spidroins consist of 90–350 amino acids major amino acids in the spider silk proteins are alanine 29.36%, glycine 36.5 % and 4.33% Serine also proline (3.6%) are present in significant quantities as shown in Table 2 and Figure 3. Normandeauw J. et al., 2014 was reported that, there are two primary features presented in the protein Infrared spectrum, one being the Amide I band which falls into the range of 1600-1700 cm-1 and the other being the Amide II band falling into the range of 1500-1600 cm-1[18-

20]. As one can observed from Table 2, the spider Bark silk is exceptionally rich in glycine and alanine, which imparts high strength and flexibility. In contrast, wool and collagen contain higher amounts of proline and other amino acids, contributing to elasticity in wool and structural stability in collagen. It is important to note that these values may slightly vary depending on the species, silk gland type, and environmental factors.

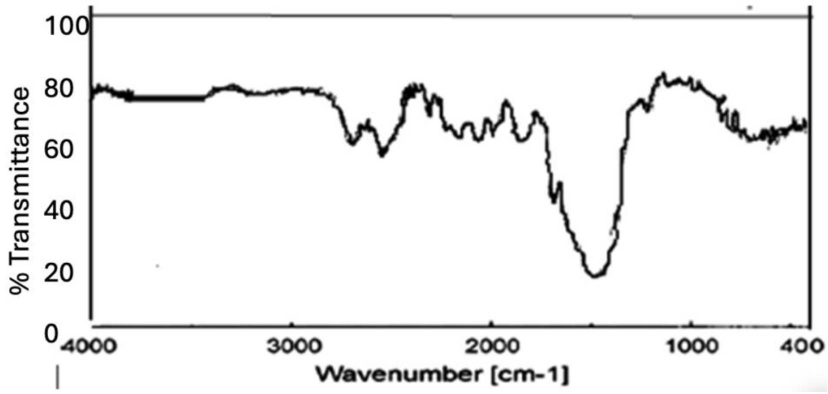

Figure 3. FTIR Analysis of Spider Silk Fiber.

Table 2. Amino acid composition (mole %) of Spider Bark silk and Other Commonly used Protein Fibers (for wool and Collagen, Saravanan D., 2006, Kaplan et al., 1997).

Amino Acid	Spider Bark Silk (%)	Silk Fibroin (%)	Wool (%)	Collagen (%)
Glycine (Gly)	45–50	43–45	12–15	33
Alanine (Ala)	20–25	30–31	6–7	11
Serine (Ser)	3–5	12–13	4–5	3
Proline (Pro)	2–3	0.5–1	14–15	10
Valine (Val)	3–4	0.5–1	3–4	2
Leucine (Leu)	0.5–1	0.5–1	3–4	1
Glutamine (Gln)	1–2	0.5–1	3–4	1
Tyrosine (Tyr)	0–1	5–6	3–4	1
Arginine (Arg)	1–2	0.5–1	5–6	1
Other Amino Acids	1–3	5–7	15–18	37

3.3. Mechanical Properties of Spider Silk Fiber

Spider silk fibers are typically semi-crystalline and are among the strongest, toughest, and most stretchable biological protein fibers due to their unique structure. As observed from Table 3 and Figure 4, the mechanical properties of spider silk fibers vary both from species to species and from specimen to specimen. For this reason, all mechanical property results in this research were reported as average values. Frank K. Ko et al. (2006) also confirmed this phenomenon, noting that the mechanical properties of spider silk fibers vary across species and individual specimens. Spider silk fiber is sensitive to moisture; when exposed, the fiber undergoes shrinkage, a phenomenon known as supercontraction, which affects its overall mechanical properties [21-25]. In this study, experimental testing of spider silk fibers was conducted using simple elongation at a strain rate of 100% per minute with a gauge length of 1.25 cm. The mechanical properties of spider silk fibers were compared with other commonly used textile fibers, as shown in Table 3. As observed from Table 3 and Figure 4, spider fibers exhibit good mechanical properties, including elongation at break, with a balanced combination of strength and toughness. The test results revealed that the average tensile strength and elongation at break of Bark Spider silk fiber were 1.21×10^8 N/m² and 30–41%, respectively, as shown in Table 3. The initial modulus of the spider fiber was recorded as 8.05 GPa, and the failure stress was 0.69 GPa at a breaking elongation of 28%. The average elongation and stress values were 8.5 mm and 1.2 N/Tex, respectively, as shown in Figure 4. The elongation at break of spider silk fiber was higher than that of silk and exceeded the values for commercially known steel and Kevlar fibers. This enhanced stretchability is attributed to the presence of glycine in its morphological structure. The glycine molecules are arranged in a disordered manner, which contributes to the fiber's elasticity and ability to stretch. Moreover, the maximum time to fiber breakage was almost identical across samples, as shown in Figure 4. Overall, the experimental results confirmed that spider fibers possess good strength, though they are less strong and tough than silk fibers.

Table 3. Mechanical Properties of Spider Silk and Other Commercially Used Fibers.

Type of Fibers	Elongation at break (%)	Tensile Strength (N/m2)	Reference
Spider silk	30–41	1.21×10^8	-
Silkworm silk	15–35	6×10^8	Yunqing Gu et al., 2020
Nylon	18–26	5×10^8	
Kevlar	2–5	4×10^9	
Steel	8	1×10^9	

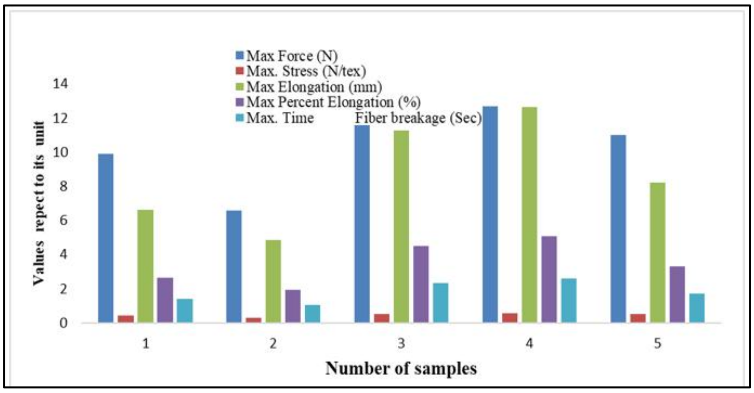

Figure 4. Mechanical Properties Analysis of Spider Silk Fiber.

3.4. Medical application of Spider Silk Fiber

Spider silk fibers (SSF) exhibit strong antibacterial activity, making them highly promising for medical applications such as wound dressings and implant coatings. The fibers are naturally coated with small bioactive peptides that inhibit the growth of microorganisms. As shown in Figure 5a, microorganisms readily colonized the surfaces of untreated materials over a period of 10 days. In contrast, surfaces treated with SSF (Figures 5b and 5c) showed markedly reduced microbial growth. The effect was more pronounced in Figure 5c, where the spider silk webs were left intact on the surface, resulting in minimal microbial colonization and a clearly defined inhibition zone. This antibacterial activity is attributed to the combination of the acidic nature of spider silk and the presence of antimicrobial peptides, which together create an unfavorable environment for microbial proliferation. These results demonstrate that SSF not only prevents microbial adhesion but also effectively inhibits growth over time, highlighting its potential as a natural, biocompatible antimicrobial material for medical applications [24].

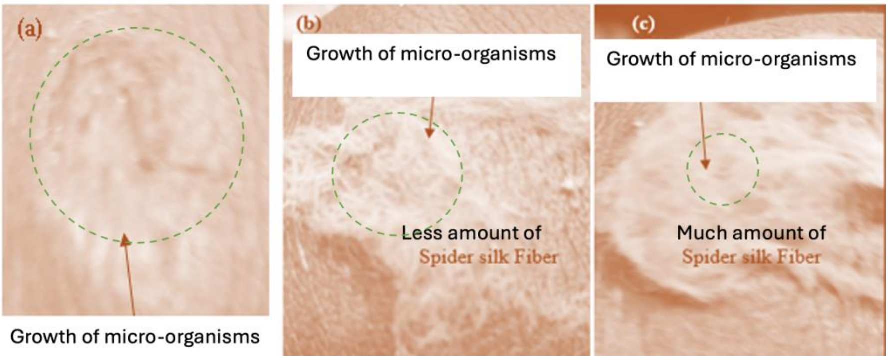

Figure 5. (a) Growing areas covered by microorganism, medical application of Spider silk fiber matt covered on the micro-organism respective with SSF amounts (b) After 5 days and (c) After 10 days.

4. Conclusions

Spider silk fiber is a biocompatible protein natural fiber obtained from spider worm. Spider silk fiber is sensitive to moisture, and affect the overall mechanical properties of the fiber. Moreover, the physical and mechanical properties of the spider fiber were significantly depended on the arrangement of amino acid and hierarchal structure of the protein. The experimental results revealed that, the elongation at break of spider silk fiber was higher than silk and it was higher than commercially known of steel and Kevlar fiber. Also, this experimental results were approved that, spider fibers had good strength but has less strong and. tougher than silk fiber. Moreover, Spider fibers having potential of antibacterial activity could provide a lot of medical applications. SSF was naturally coated small peptides and these peptides had an anti-microbial role for spider silk fibers. But this experimental work also observed that, natural spider fibers obtained from the web had a very low yield and could not satisfy the actual application requirements in medical application. Generally, this research work would try to show same directions about its biophysicochemical properties and future potential of spider silk fibers as antimicrobial fibers in medical sectors.

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Data Availability

The data supporting the findings of this published article are provided to journal as a supporting data and can be requested from author as well.

Conflicts of Interest

The authors declare no conflict of interest.

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