Spider silk: structure, function and uses

ASSIGN BUSTER

Spider silk, also known as gossamer, is a fiber spun by spiders. Spider silk is a remarkably strong. Its tensile strength is comparable to that of high-grade steel. The term silk normally refers to a wide range of continuous filaments spun by the several species of Lepidoptera and Arthropoda, used for building structures for various purposes including prey capture. Silk filaments spun by spiders and silkworms possess superior properties than other silk producing insects and more than 2500 orb weaving species existing worldwide [1 – 4]. Spiders have six or seven sets of glands, each producing a different fiber. These glands remained undifferentiated, early in the evolution [4 – 7]. The spinnerets, microscopic tubes originating from glands, are classified into major and minor ampullate. The term " ampulla" is used to describe the distal part of the secretary zone [8]. Unlike synthetic polymers, the biopolymers are composed of numerous monomers arranged in a strictly controlled manner [9]. Many attempts have been made in the past to harvest and convert spider silk filaments into fabric form [4, 10, 11]. Scientists have been hard at work attempting to marshal the power of spider silk for a range of medical applications-including wound-care applications; suture materials; muscle, bone, cartilage, tendon, and ligament repair scaffolds. Spider silk possesses mechanical attributes such as very high tensile strength and elasticity, making it one of the toughest fibers known to man. The problem is that spiders don't produce enough silk to render it marketable for mass human use.

SPIDER WEB AND TYPES OF SPIDER SILK: Prior to the exploration of the structure and properties of spider silks, construction and design of webs have been the major area of focus. The spider webs can take a variety of forms but the most common type is the orb web. Different families of spiders like Araneus, Nephila builds orb web and other families of spiders construct tangle and sheet webs [33, 35]. Orb-web spiders invest little energy in searching for prey. It spends most of its time synthesising silk and constructing webs.

An orb web has several spokes laid outward from a common origin. However, this varies amongst the various species of spiders [31]. The orb webs are often constructed with an orientation to avoid being damaged due to the air drag caused by prey capture [24]. In a three dimensional web, the energy required to stop a moving insect is dissipated mainly by breaking some of the strands. In a two dimensional orb web, it is achieved through stretching the spiral threads [29]. Due to high-energy requirement in protein synthesis, only the damaged parts of the web are reconstructed instead of the whole web. Large portions of the web are repaired through the enzyme digestion and recycling. Based on the vibrations of the strands, the spider locates the prey accurately.

The orb-weaving spiders are able to synthesize as many as seven different types of silk [13-15] including dragline by drawing liquid crystalline proteins from separate gland-spinneret complex. The perfume-coated dragline helps to find their mates, swing from place to place, store food, eggs and for reproduction. Capture threads produced by the flagella form glands of Nephila Clavipes is highly compliant. Both Araneus and Nephila coat their capture threads with an aqueous solution that forms sticky droplets which enhances damping and harvest’s water from air [25]. Its principal function is to absorb and dissipate the kinetic energy of captured flying insects. [3]. The chemical composition of the aqueous solution of the adhesive spiral varies among the species qualitatively and quantitatively. The variation is mainly due to physical environment, diet, web recycling, and onto genetic changes in the web chemistry.

SPINNING OF SPIDER SILK: Many spiders are active at night and their colorations are usually orange, brown, grey and black, to reduce the spiders' visibility during day time. Silk secreting systems of spiders and insects are homologous and linked to the crural gland and cuticular secretions [6]. Cephalothorax of the spider attached to an unsegmented abdomen, which has spinnerets at the posterior end [33]. N. clavipes spider has three pairs of spinnerets namely, anterior lateral, posterior lateral and posterior median. The largest major ampullate gland secretes dragline silk protein, exits from the anterior lateral spinneret. Secretions of proximal region and the distal region together form spider silk. Proximal region secretions are rich in tyrosine residues, sulfhydryl linkages and acidophilic nature. They form core of the silk while secretions of distal zone form coating of the fiber, which lacks tyrosine and sulfur contents.

A mature Nephila produces dragline silk fiber at approximately 1 cm/sec during web construction and can increase up to 10 times faster during a rapid descent [52]. Spider silk spun under water displays greater stiffness and resilience compared to silk spun naturally in air [53]. The diameter of the silk can be controlled by the valve located at the end of the duct [47]. The spiders have the ability to withstand temperature variation of up to 30oC and humidity variation of up to 70% [20]. Spiders can easily modify the spinning conditions by their moving speed, building the webs in different times in a day. Spinning speed has less influence on the diameter of the filament when compared to the temperature even though its influence on toughness.

COMPOSITION OF SILK: Variability in silk spun by the spiders exists at different levels such as in inter-specific (between species), intra-specific (within same species) and intra individual levels [54]. The factors that affect variations in silk structure and properties include body dimensions, body weight, rate and temperature of reeling and spinning direction [17, 25]. Composition of silks produced by herbivorous spiders is rich in Glycine, Alanine and Serine. This type of silk can be predicted to some extent. However, the silk produced by predatory spider, cannot be predicted due to the different types of prey [40, 55]. Dietary compositions of herbivorous spiders are energy rich and poor in protein content whereas the diet of predatory spiders is more diverse and rich in protein. Competition for limited or fluctuating supplies of amino acid perhaps has resulted in the evolution of two different kinds of glands to secrete protein glues and silk fibroin. The spider produces the thread on a very strict energy budget using liquid crystalline polymer.

STRUCTURE AND PROPERTIES: Spider silk has drawn attention from all the sections of engineering due to its superior properties when compared to existing fibrous materials such as the silkworm silk. Spider silk cannot be compared with silkworm silk. This is because spiders are difficult to raise in large numbers and their silk lacks the lustre of silkworm silk. The chemical compositions of various silks vary with the type of function they are intended to perform. In addition to the fibroin, other classes like glycoprotein , inorganic salts, sulphur containing compounds, amino acids, and ionic forms of amines are also present in the spider silk [69, 70]. Presences of these chemicals play crucial roles in identification of species, regulation of water content of the web and protection against microorganisms. Presence of 12-methyltetradecanic acid and 14-methyl hexadecanoic acid in less amounts impart antimicrobial properties to the spider silk. Wax like esters are also present in the surface of the spider silk.

Macroscopic Structure of Dragline Silk: Dragline spider silk is golden yellow in color and has circular cross section with a mean diameter of about 7 Î¼m [19, 38, 54]. It lacks glue-like protein, similar to that of silkworm silk, as it’s associated with dragline fiber [56]. The dragline spider silk consists of semi crystalline polymeric structures with numerous small crystallites between amorphous regions. The mechanical properties of the dragline silk are highly influenced by the composition of the amino acids, insect size, diet, body temperature and drawing speed [99, 124]. The breaking strength of silk increases linearly with increasing spider weight and breaks at stress of about six times the spider’s weight [47, 100, 129]. The average tensile strength of the dragline of Nephila clavipes is almost three times that of Bombyx mori (1. 3 & 0. 5 GPa, respectively). Tensile strength of spider silk reduces, when it is subjected to acidic rain and UV radiation [133]. Spider silks can undergo large tensile and compression deformations. The ability of spider silk to resist transverse compression is lower than that of many textile fibers like Kevlar 29, nylon 5, polyester and wool.

REGENERATED SPIDER SILK PROTEIN BY ARTIFICIAL ROUTE:

Forced Silking (Reeling) of Spider Silk

Reeling devices have been developed for forced silking of dragline from the glands of anaesthetized Nephila clavipes [78, 115, 140, 141] to reel about 3-5 mg of silk in one session. Splicing of silk genes into two different cell lines have been tried in the past using bovine mammary cells and hamster kidney cells, to produce large volumes of recombinant proteins [49, 135]. Successful sequencing of genes of the flagella form silk of tropical spider Nephila clavipes and N. madagascariensis has been achieved lately [39]. Recombinant DNA technology for microbial proteins [144, 150, 151] appears to be advantageous compared to that of chemical synthesis due to low cost, rapid preparation and absence of by-products. A team of researchers at the University of Notre Dame (Notre Dame, IN) the University of Wyoming (Laramie), and Kraig Biocraft Laboratories Inc. (Lansing, MI) have succeeded in producing transgenic silkworms. The advantage of these animals is that they can spin artificial spider silk with strength and flexibile attributes similar to those of native spider silk. Until this breakthrough, only very small quantities of artificial spider silk had been produced in the laboratories. Kraig Biocraft believed these limitations can be overcome through use of recombinant DNA. This biotechnological approach can be used to produce silk fibers with a broad range of physical properties or with predetermined properties optimized for specific biomedical or other applications.

From the known sequence of the spider silk protein, genes are constructed and expressed using E. Coli as the host, which has been successfully used earlier for silkworm silk [160]. Genes of spider dragline silk have been inserted into mammary gland cells along with regulatory elements. Insertion of the genes into eggs of single cell goat has been tried. This was purposely done to produce water-soluble silk protein [154, 156, 165]. Few milligrams of genetically engineered silk like protein has been successfully produced based on the sequence of spider protein [155].

APPLICATIONS: Though availability of the dragline silk is limited, it is widely used in defence [4,] and medical [11] applications. Structural similarity and comparable properties of dragline and Kevlar [127, 180] makes it more attractive for applications where high performance, in terms of physical properties is in demand.

Until World War II, spider silk was used as crossed-hairs in optical devices including microscopes, telescope and bomb guiding systems [4]. Silk strands of the web have an ability to elongate when an insect is caught, convert the prey’s momentum i. e. kinetic energy into heat, and dissipate about 70% of the converted energy. The web also gently rebounds so as not to catapult the insect back out. This ability to dissipate energy at very high strain rates makes spider silk suitable for body armour system and ideal for ballistic protection [131, 140]. Though biodegradability is a helpful aspect for sutures, it is as unwanted in high performance applications such as bulletproof vests. A very low glass transition temperature of -50o C to – 60o C enables it to absorb sudden shocks at low atmospheric temperature and makes the spider silk suitable for parachute applications. However, super contraction in water is undesirable for use in the fabrication of parachutes [174, 175].

Earlier use of spider silk in the form of web, rather than a fiber, includes wound dressing to help blood clot and fishing nets. Spider silk protein can be used to coat the medical implants for better performance. Surgical thread, biomembranes and scaffolds for tissue engineering are the possible areas of application in biomedical and biomaterial fields. Due to low inflammatory potential of silk proteins and antithrombic nature, recombinant spider silk has potential applications in sutures for eye surgery, artificial tendon and ligaments for knee construction. Spider silk with higher safety co-efficient can be used in structural applications like elevator ropes, bridges and pillars [100].

CONCLUSION

The dragline silk offers excellent physical and chemical properties that can withstand adverse and extreme conditions than many of the existing natural and synthetic fibers. Though the chemical synthesis seems to be unfruitful in many aspects, the recombination method of producing the spider silk using biological hosts proves to be a viable option for producing the spider silk in a large scale. In spite of various successful attempts made in the production of dragline silk in the laboratory scales, controlling the molecular conformation and their aggregation during the spinning for achieving properties similar to the native fiber still remains as a challenge to be addressed through future research.