# Applications of Silk Based Materials
# การประยุกต์ใช้งานวัสดุที่มีไหมเป็นส่วนประกอบ

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## บทคัดย่อ

มีการนำเส้นไหมหม่อนมาใช้ในการผลิตเครื่องนุ่งห่มและเป็นชีววัสดุทางการแพทย์คือ ไหมเย็บแผลมาหลายร้อยปีแล้ว คุณสมบัติที่ดีเยี่ยมของเส้นไหมทำให้มีการนำไปใช้งานในด้านอื่นเพิ่มมากขึ้น จากรายงานการศึกษาวิจัยต่างๆ พบว่า ไฟโบรอินของไหมสามารถออกแบบให้มีรูปแบบที่หลากหลาย โดยสามารถผสมกับชีววัสดุอื่นๆ ได้เป็นอย่างดีทำให้เกิดความเหมาะสมต่อการใช้งานที่จำเพาะ ทั้งในส่วนของโครงสร้างและบทบาทหน้าที่ ทำให้สามารถนำไหมไปใช้งานได้แตกต่างกันขึ้น เช่น เครื่องสำอาง สารเติมแต่งในอาหารและเครื่องดื่ม สารเคลือบป้องกันแบคทีเรีย หรืออุปกรณ์เสริม ปัจจุบัน การศึกษาวิจัยที่เกี่ยวกับไหมมุ่งพัฒนาประเด็นไปในการเตรียมไหมให้เป็นชีววัสดุสำหรับนำไปใช้ในงานด้านวิศวกรรมเนื้อเยื่อและระบบนำส่งยา

**คำสำคัญ:** การประยุกต์ใช้ ระบบนำส่ง ไฟโบรอิน วัสดุ ไหม วิศวกรรมเนื้อเยื่อ

## Abstract

Silk fibers from silkworms have been used in textiles production and as biomedical suture material for centuries. The excellent properties of this fiber are attractive for other applications. More recent studies suggest that the silk fibroin exhibit additional rationale for designing various forms. Additionally, silk fibers have comparable biocompatibility with other commonly used biomaterials to tailor for specific applications in both of structural and biological functions. This helps to apply silk in different fields like cosmetics, food and drink additives, antibacterial coating or supplementary devices. To date, silk is gradually focused to address as biomaterial for tissue engineering as well as drug delivery system applications.

**Keywords:** application, drug delivery system, fibroin, material, silk, tissue engineering

## Introduction

Silks are fibrous protein polymer that is spun by some insects including silkworms[1]. Silks differ widely in composition, structure and properties depending on coming source. Each silk has a different amino acid composition and exhibits mechanical properties tailored to their specific function. Silk represents the strongest natural fiber and has a long medical history as surgical sutures[2]. Recently, silk has been used for cosmetics, medical materials as well as food and drink additives[3]. Silk consists of the distinctive biological and functional properties[4]. It can also be prepared in various forms

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depending on its application[5]. According to its excellent properties, silk is now being focused on new biomaterials for biomedical applications such as tissue engineering[6] and drug delivery system[7]. This review aimed to report on silk including its history, life cycle, compositions, and properties. In addition, various regenerat fons silk and its applications were studied

## General Comments about silk

Silk is a natural fiber produced by a variety of insects including silkworms, which has been used traditionally in textiles for thousands of years[8]. With history records, China is the world's biggest producer and exporter of raw silk. However, silk is still produced by countries around the world in smaller quantities. Silk is generally produced from two varieties of insect in order Lepidoptera; mulberry (Bombycidae) and wild or non-mulberry (Saturniidae) silks. The last group grows in India, China, and Japan. Silkworms live a very short time (about 45-60 days). At the fifth instars larva, liquid of silk solution was secreted from two large glands in the silkworm emerge from the spinneret. The silk glands have 3 regions called anterior, middle (secretes sericin) and posterior (secretes fibroin). A single silk filament reveals triangular in shape as shown in Figure 1, and the light reflecting off it gives its shine. The silkworm spins its cocoon over three days. Silk filament is strong, as strong as steel of the same thickness, and much stronger than cotton or wool. It is also less in density than cotton, wool or nylon which is highly moisture absorbent.

Each silk fiber consists of at least 2 main proteins which are structural protein fibroin and the water-soluble glue-like protein sericin that bind the fibroin fibers together as shown in Figure 1. Silk fibroin (SF) filament consists of heavy (~350 kDa) and light chain (~25 kDa) polypeptides connected by a disulfide link[9]. The SF is a highly insoluble region with the amino acids which are glycine, alanine and serine forming antiparallel b-sheets in the spun fibers[10]. However, both fibroin and sericin proteins composed of the same 18 amino acids, but are varies in ratios[11] as summarized in Table 1. Variability can be influenced by the dietary intake of the animal and the environmental conditions during the spinning process[12]. In addition, silk may contains of bulky amino acids such as glutamic acid, aspartic acid, proline and valine[13]. These amino acids are responsible for the formation of the amorphous part of the silk, which in turn affects the overall physical properties of the silk in association with the crystalline region. Silk fiber composes of 75-83% silk fibroin, 17-25% sericin, 1.5% waxes and 1-2% of others such as hydrocarbon by weight[14]. Silk fibers have higher tensile strength than glass or synthetic organic fibers, good elasticity, and excellent resilience[15]. It is normally stable up to 140°C and the thermal decomposition temperature is greater than 150°C. The densities are in the range of 1320-1400 g/m$^3$ and 1300-1380 g/m$^3$ with and without sericin, respectively[16]. Silk is degradable but over longer time periods due to proteolytic degradation[17]. It loses the majority of their tensile strength within 1 year *in vivo*, and fails to be recognized at the site within 2 years[18].

## Processing silk proteins

Humans were known to use silk thousands of years ago. Raw silk fiber requires little processing prior to applying it. The one process that very important to get the pure silk fibroin is an excluding sericin protein called "degumming process". The sericin protein is generally composed of polar or bulky amino acids which are destroyed by various substances such as alkali, acid, hot water, salt or protease enzymes[19]. In the past, silk had been firstly used almost for textile production and as suture for medical application[20]. In Thailand, an important clue that indicated the importance of silk is the silk debris year over 3000 years found in Ban Chiang, the World Heritage.

## Regenerated of silk fibroin

Several forms of silk-based biomaterials can be produced from silk solutions as shown in Figure 2.

However, for an important step in order to prepare alternative material morphologies or composite materials, SF is typically dissolved into an aqueous solution. There are many methods used for dissolving the SF including concentrated aqueous solutions of inorganic/

organic salts, fluorinated solvents, ionic liquids or strong acids[21]. Inrevious reports, regenerated silk can be performed into various kinds depending on applications, and by different methods. These are example forms and methods used for preparation. Silk films are prepared by cast or layer-by-layer deposition of silk aqueous[22]. Hydrogels of SF are formed via sol–gel transitions by sonication, vortexing, or the presence of acid and/or ions[23]. Nanofibers of SF can be prepared by electrospinning[24]. Silk-based 3D scaffolds are attractive biomaterials for tissue regeneration and immobilization or loaded various substances[25]. Silk-based nanoparticles have been also investigated[26]. Silk fibroin microspheres were processed using spray-drying[27] or water-in-oil emulsion solvent diffusion method[28]. Nanolayer coatings of silk fibroin have been prepared using the stepwise deposition method[29].

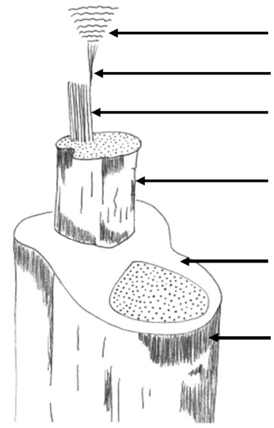


**Figure 1** Structure of the raw silk fiber.

**Source:** Adapted from Sonthisombat and Speakman.[30]

**Table 1** Amino acid compositions in silk fiber extracted from mulberry silk (*Bombyx mori*) (g/100 g of fiber).

| Amino acid | Fibroin | Sericin |
|---|---|---|
| Glycine | 42.9 | 13.5 |
| Alanine | 30.0 | 5.8 |
| Serine | 12.2 | 34 |
| Tyrosine | 4.8 | 3.6 |
| Aspartic acid | 1.9 | 14.6 |
| Arginine | 0.5 | 3.1 |
| Histidine | 0.2 | 1.4 |
| Glutamic acid | 1.4 | 6.2 |
| Lysine | 0.4 | 3.5 |
| Valine | 2.5 | 2.9 |
| Leucine | 0.6 | 0.7 |
| Isoleucine | 0.6 | 0.7 |
| Phenylalanine | 0.7 | 0.4 |
| Proline | 0.5 | 0.6 |
| Threonine | 0.9 | 8.8 |
| Methionine | 0.1 | 0.1 |
| Cystein | Trace | 0.1 |
| Tryptophan | - | - |

**Source:** Adapted from Zhao and Asakura.[11]

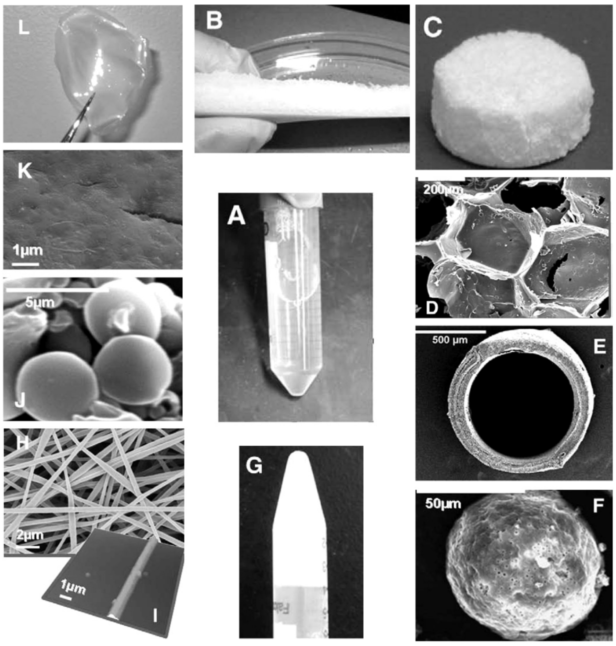


**Figure 2** Silk-based biomaterials processed from silk solution (A), silk foam (B), silk scaffolds and C), scanning electron microscope image of porous structure of scaffold (D), silk tube(E), microsphere coated with silk layers (F), silk hydrogel (G), silk electrospun fibers (H), atomic fluorescence microscopy image of single electrospun fibers of silk (I), silk-based microspheres (J), surface of silk films (K), and silk film (L)[31].

## Silk based composites with biodegradable polymers

It is difficult to find excellent properties for all our needs only in single material, especially from natural polymer. Nowadays, researchers attempt to construct the material that composed the best properties Blending or composite polymer is a method used for solving this problem. SF has been blended with other materials both synthetic and natural polymers. However, in the last decades, biodegradable polymers have been chosen and gradually increased for application[32]. The reason is due to avoid of second time of surgeon after tissue recovering as well as the side effects of materials on cell. Silk-based composites or blending polymers was increasingly developed and distributed to various fields, especially biomedical and pharmaceutical approaches[33].

Indeed, silk-based composite fibers were found to improve their properties for textile applications and since then a variety of other materials morphologies have been prepared based silk proteins. Biodegradable synthetic polymers are attractive for many material applications, particularly when considering they affect fewer environmental hazards. Among the biodegradable polymers, synthetic types were firstly used to blend with silk fibroin. Many kinds of the synthetic biodegradable polymers were reported, especially polyester and copolyesters[34-37].

Now silk combinations with a variety of natural polymers is attracted by many researchers. Protein-based material has been used for blending with silk fibroin such as collagen, enzymes, fibroin from different species, gelatin, green fluorescent protein, growth factors, keratin and sericin. The protein blended silk fibroin helps to improve some properties of the fibroin products which are interacted with the silk fibroin via hydrogen bond formation[33].

Beside the protein-based materials, polysaccharides are an important group that is used for modification of silk fibroin properties. This material is abundant in nature and low cost.

Many kinds of polysaccharide that are used as composites with silk fibroin have been reported. Alginate, a linear polysaccharide, is used extensively in biomedical, food and textile industries. The alginate helps to improve the mechanical properties, compressive modulus as well as water absorption of the silk fibroin[38]. Cellulose is the most natural polymer found in the world. It is widely used in textile industry due to it is cheap, biodegradable and moisture absorbent. Silk fibroin blended with cellulose has increased of its mechanical strength since the cellulose enhanced the formation of hydrogen bonds resulted to increase of b-sheet structures[39]. Chitin, a main component of the cell walls of fungi, and the exoskeleton of arthropods and insects, is applied in adhesives, food and various biomedical/filtration technologies. Previous report was found that the mechanical properties of the silk fibroin and chitin fibers were poorer than those of either silk or chitin alone, but potentially usable in the textile industry[40]. Chitosan is a linear polysaccharide produced by deacetylation, and is utilized in agriculture, biomedicine and filtration technologies. Chitosan used for improving the flexibility or hydrophilic of the silk fibroin while the silk fibroin enhanced the mechanical properties and water insoluble of the chitosan[41]. Hyaluronic acid is a glycosaminoglycan. It has been used in cosmetics and medical applications. Mixing with the hyaluronic, the compressive modulus of silk fibroin was increased[42].

## Applications of silk-based materials

Silk has been used in the textile industry over centuries[43]. It has been also used as sutures due to their strength, biocompatibility and low immunogenicity. Non-woven mats of silk fibers have been constructed via electrospinning and are currently being investigated for application as wound dressings[44] and antibacterial such as [*Escherichia coli, Pseudomonas aeruginosa* and *Staphylococcus aureus*][45]. Hydrogels of SF demonstrated to promote wound healing[46]. Electrospun silk fibers, microspheres, or films or foams with hydroxyapatite nanoparticles were demonstrated to support cell adhesion and proliferation of many cells[33]. Silk films are promising candidates for biocompatible coatings for biomedical implants. Coating biomedical implants with silk films shows potential their surfaces with anticoagulant properties, or inhibit/promote cell adhesion[47]. Silk has been also used as anticoagulants for control release application[48]. Microspheres coated with silk fibroin have been applied for enzymes, drug and active molecule encapsulations[49] and membrane-permeation controlled[50]. Silk has also been applied in areas as diverse as currency, hunting (bow strings, cross-hairs, fishing lines or nets) and paper[51].

Silk in particle form has been commercially used in various fields such as ingredients for cosmetic products and nutritional foods. Furthermore, silk powder can be used for surface coating or treatment of fiber, fillers in films, ink, wound care and enzyme immobilization[52].

## Conclusion

Silk is a kind of natural fibers spun by silkworms. According to its excellent properties, silk-based materials have been used as medical sutures and textile production for centuries. It has also been explored for other applications such as a biomaterial for cell culture and tissue engineering, delivery of bioactive molecules and drugs in slow, sustained and controlled release, antibacterial coating, food and drink additives, cosmetics and part of instruments since it can be generated into various forms which fitted for applications.

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