Recent Innovations in Silk Biomaterials

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Abstract: Silk contains a fibre forming protein, fibroin, which is biocompatible, particularly after removing the potentially immunogenic non-fibroin proteins. Silk can be engineered into a wide range of materials with diverse morphologies. Moreover, it is possible to regenerate fibroin with a desired amount of crystallinity, so that the biodegradation of silk materials can be controlled. These advantages have sparked new interest in the use of silk fibroin for biomedical applications, including tissue engineering scaffolds and carriers for sustained release of biologically active molecules. This article summarizes the current research related to the formation of silk materials with different morphologies, their biocompatibility, and examples of their biomedical applications. Recent work on the preparation of silk particles by mechanical milling and their applications in silk composite scaffolds is also discussed.

Keywords: Silk fibroin, powder, composite, morphology, application.

1. Introduction

Silk consists of fibrous proteins that are stored as a liquid in silk producing arthropods (such as silkworms, spiders, scorpions, mites and bees) and are spun into fibres at secretion [1]. Amongst various silk species, silkworm and spider silk fibres have been widely studied for their structure, processing, and functional properties. About 90% of commercial silk fibres used in the textile industry come from Lepidopteron silkworms from the family, *Bombycidae* [2]. In the textile industry, it is commonly referred to as Mulberry silk. *Saturniidae* is another class of Lepidopteron silkworms that produce commercial silk fibres such as Tasar, Eri and Muga.

Apart from their long history as luxury textiles, silk has also been used in the human body in the form of suture material [3]. A study by Minoura *et al.* [4,5] has suggested much wider application prospects for silk. Their study showed that silk fibroin of *B.mori* and *A.pernyi* was equal to or even better than collagen in supporting attachment and proliferation of murine L-929 fibroblast cells. The results have generated enormous interest in the ensuing years to examine silk fibroin for various biomedical and healthcare applications through *in-vitro* or animal model studies. Native silk fibre suture is a Food and Drug Administration (FDA, USA) approved biomaterial. Recently, regenerated silk has also been approved by the FDA for human clinical tests.

2. Different forms of silk biomaterial

Silk biomaterials can be prepared directly from silk fibres, or reconstituted from silk fibroin solution. An alternate way is to convert silk fibres into ultrafine particles through milling. Figure 1 shows a schematic diagram of processing silk fibres into various forms of diverse morphologies [6].

2.1 Native Silk fibre based structures

Degummed silk filaments in the form of twisted structures, such as wire-rope, cable, braided, and textured yarns have been analysed for potential biomedical applications [7]. Silk filaments can also be used to construct nonwoven structures as a cell supporting template, by partially dissolving silk fibres [8,9]. Random arrangements of filaments in a cocoon can be preserved during degumming to design a porous nonwoven silk mat for cell seeding [9]. An alternate way of using silk filaments directly in tissue engineering is making a knitted structure [10]. Such knitted structures have been used to reinforce 3-D porous tissue engineering scaffolds for improved mechanical properties [11].

2.2 Regenerated Silk Biomaterials

Silk fibres can be dissolved by using a highly concentrated solution of chaotropic salts followed by dialysis to prepare an aqueous silk solution. Alternatively, ionic solvents have been used to dissolve silk fibres [12-14]. Silk aqueous solutions form gels during prolonged storage (months), particularly when silk concentration is high [15]. Hence, silk aqueous solutions are normally lyophilized for the purpose of

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storage and further processing. Lyophilized silk is amorphous in nature and can be reconstituted into dope using different organic [16-20] or acidic solvents [21]. A number of different regenerated products can be formed using silk fibroin aqueous solutions or reconstituted dope. The following forms of regenerated silk have been examined in recent years:

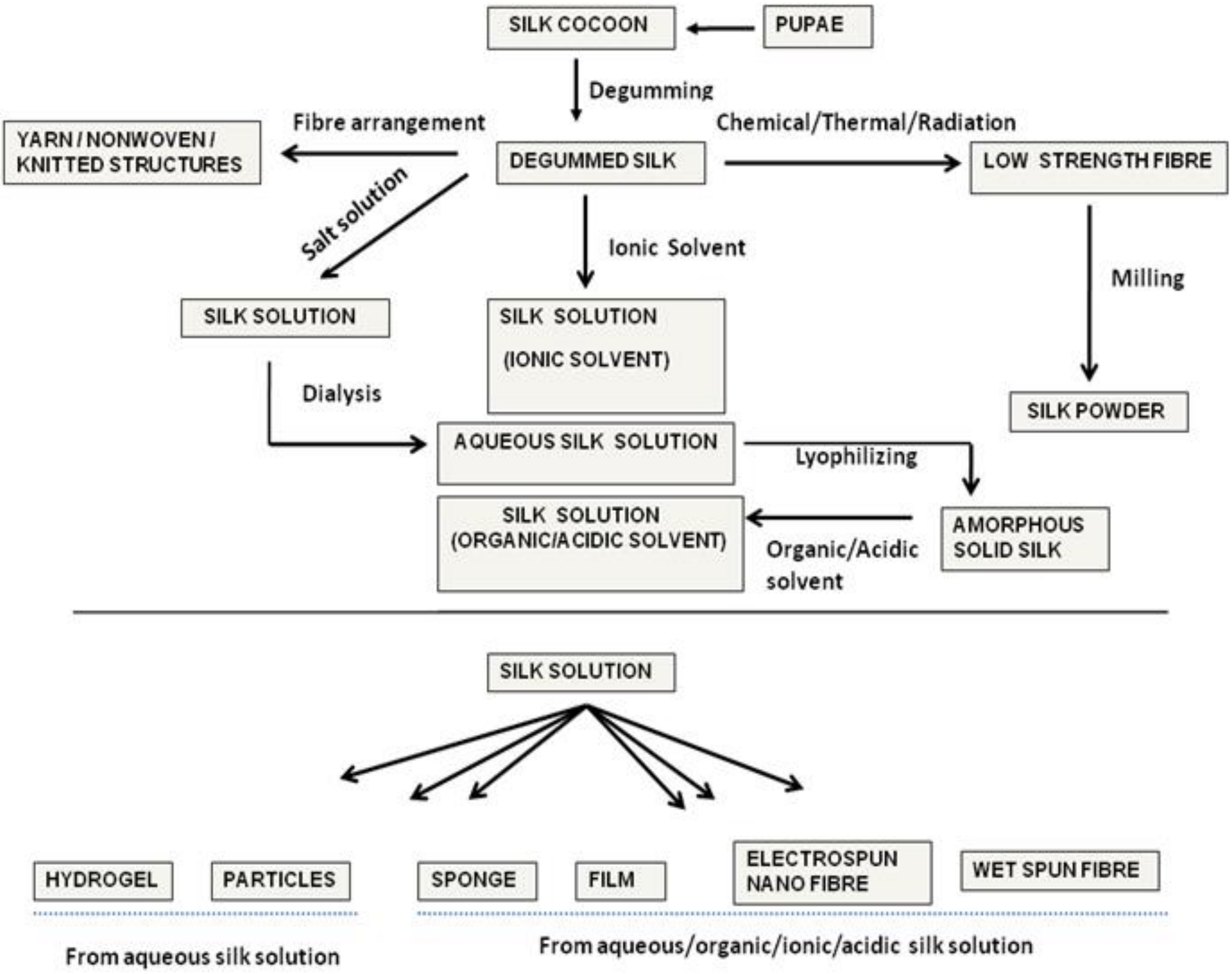

Figure 1 Process pathways for the different forms of silk biomaterial

2.2.1 Silk films

Silk fibroin films can be prepared by casting [13,21-24], spin coating [13], Langmuir-Blodgett (LB) [25] and layer by layer deposition [26-28]. Recently, patterned silk films have been developed as a cell supporting template for improved cell proliferation [13,29]. High oxygen and water vapour permeability of silk films is important for their wound healing applications [30,31].

2.2.2 Regenerated silk fibres

Electrospinning has been used to create silk nonwoven mats with a large surface area and a porous structure that are useful for cell seeding [32,33] and as separation membranes [34]. More recently, 3-D constructions of silk nanofibres have been used as blood vessel grafts and nerve guides [35,36]. Likewise, wet spinning of silk has been examined to produce silk fibres with physical and mechanical properties otherwise not available in its natural form. Producing regenerated silk with properties comparable to native silk fibres has been a major challenge. However, in recent years, it has been shown that by appropriate post spinning drafting, regenerated silk fibres having superior mechanical properties could be produced [37]. Likewise, it was also demonstrated that by optimising the rate of coagulation during extrusion and through post spinning stream annealing of extruded fibres, the