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Electrospinning: A fascinating fiber fabrication technique

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ABSTRACT

With the emergence of nanotechnology, researchers become more interested in studying the unique properties of nanoscale materials. Electrospinning, an electrostatic fiber fabrication technique has evinced more interest and attention in recent years due to its versatility and potential for applications in diverse fields. The notable applications include in tissue engineering, biosensors, filtration, wound dressings, drug delivery, and enzyme immobilization. The nanoscale fibers are generated by the application of strong electric field on polymer solution or melt. The non-wovens nanofibrous mats produced by this technique mimics extracellular matrix components much closely as compared to the conventional techniques. The sub-micron range spun fibers produced by this process, offer various advantages like high surface area to volume ratio, tunable porosity and the ability to manipulate nanofiber composition in order to get desired properties and function. Over the years, more than 200 polymers have been electropun for various applications and the number is still increasing gradually with time. With these in perspectives, we aim to present in this review, an overview of the electrospinning technique with its promising advantages and potential applications. We have discussed the electrospinning theory, spinnable polymers, parameters (solution and processing), which significantly affect the fiber morphology, solvent properties and melt electrospinning (alternative to solution electrospinning). Finally, we have focused on varied applications of electrospun fibers in different fields and concluded with the future prospects of this efficient technology.

Contents

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1. Introduction

Electrospinning, a broadly used technology for electrostatic fiber formation which utilizes electrical forces to produce polymer fibers with diameters ranging from 2 nm to several micrometers using polymer solutions of both natural and synthetic polymers has seen a tremendous increase in research and commercial attention over the past decade (Ahn et al., 2006; Lannutti et al., 2007; Hunley and Long, 2008; Reneker and Yarin, 2008). This process offers unique capabilities for producing novel natural nanofibers and fabrics with controllable pore structure (Zussman et al., 2003; He et al., 2005). Since the beginning of this century, researchers all over the world have been re-examining the electrospinning process (Cooley, 1902; Morton, 1902; Teo and Ramakrishna, 2006). This process of electrospinning has gained much attention in the last decade not only due to its versatility in spinning a wide variety of polymeric fibers but also due to its ability to consistently produce fibers in the submicron range consistently that is otherwise difficult to achieve by using standard mechanical fiber-spinning technologies techniques (Reneker et al., 2000; Schreuder-Gibson et al., 2002; Huang et al., 2003; Theron et al., 2005; Ma et al., 2005a). With smaller pores and higher surface area than regular fibers, electrospun fibers have been successfully applied in various fields, such as, nanocatalysis, tissue engineering scaffolds, protective clothing, filtration, biomedical, pharmaceutical, optical electronics, healthcare, biotechnology, defense and security, and environmental engineering (Luu et al., 2003; Subbiah et al., 2005; Ramakrishna et al., 2006; Cui et al., 2006; Wu et al., 2007; Barnes et al., 2007; Welle et al., 2007). Overall, this is a relatively robust and simple technique to produce nanofibers from a wide variety of polymers. Spun nanofibers also offer several advantages such as, an extremely high surface-to-volume ratio, tunable porosity, malleability to conform to a wide variety of sizes and shapes and the ability to control the nanofiber composition to achieve the desired results from its properties and functionality. Because of these advantages, electrospun nanofibers have been widely investigated in the past several years for its use in various applications, such as filtration, optical and chemical sensors, electrode materials and biological scaffolds (Liang et al., 2007). This technique has been known for over 60 years in the textile industry for manufacturing non-woven fiber fabrics. In recent years, there has been an increasing interest in exploiting this technology to produce nanoscale fibers, especially for the fabrication of the nanofibrous scaffold from a variety of natural and synthetic polymers for tissue engineering (Chong et al., 2007) such as polylactic acid (Yang et al., 2005), polyurethanes (Stankus et al., 2004), silk fibroin (Ohgo et al., 2003; Min et al., 2004a,b; Zarkoob et al., 2004; Alessandrino et al., 2008), collagen (Matthews et al., 2002), hyaluronic acid (Um et al., 2004), cellulose (Ma et al., 2005b), chitosan/collagen (Chen et al., 2007). Despite the several advantages offered by electrospinning, the throughput of nanofibers has been a serious bottleneck problem that limits their application. To increase the production rate of these spun fibers, a two-layer electrospinning system, with the lower layer being a ferromagnetic suspension and the upper layer a polymer solution and multiple spinnerets or nozzle systems arranged in a line/circle/matrix and a new bottom-up gas-jet electrospinning (bubble electrospinning) has been studied by various research groups (Yarin and Zussman, 2004; Theron et al., 2005; Tomaszewski and Szadkowski, 2005; Liu and He, 2007). The scale up of nanofibers through single jet is not very feasible and for various applications there is a requirement of large quantities of fibers. Various research groups have used porous hollow tube in order to get multiple jets and in this case the production rate can be enhanced by increasing the tube length and number of holes (Dosunmu et al., 2006; Varabhas et al., 2008). Apart from the huge success, advantages of electrospinning method and spun nanofibers there are still some challenges that need proper consideration. A major challenge encountered in using electrospun mats and scaffolds for tissue engineering is the non-uniform cellular distribution and lack of cellular migration in the scaffold with increasing depth under normal passive seeding conditions. The issue of cellular infiltration into the fiber architecture is rapidly gaining attention due to its potential in stagnating further applications of electrospun meshes or scaffolds in various tissue engineering applications. With the use of the conventional technique of electrospinning, nanofibers are obtained in a simple and inexpensive way. However, by this method over time there is a build-up of meshes with tremendous fiber density. It has also been reported that with the decrease of the electrospun fiber diameter there was an increase in the number of fiber-to-fiber contacts per unit length and a decrease in the mean pore radius in the mesh (Eichhorn and Sampson, 2005). Because of all these factors, there is a creation of a large size mismatch between the small pores in the structure and the larger

physical size of the cells and this in turn limits the ability of the cells to migrate and populate in the interior of the scaffolds. These limitations could potentially constrain the development and application of electrospun fibers especially for 3D tissues/organs. It is of great importance to formulate a method allowing the fabrication of cell permeable scaffolds using the electrospinning technique. Several methods have been reported in an attempt to address these issues. Ekaputra et al. (2008) have studied three methods for the improvement of cellular infiltration and also their feasibility. The first method co-electrospinning, where they have used medical grade poly (ε-caprolactone)/collagen (mPCL/Col) as the main fiber with water-soluble polymers PEO and gelatin to increase void volume in the structure with selective removal of solid material from the mesh. The method of blending with water soluble polymer offers very limited improvements compared to conventionally electrospun fibers in terms of cell infiltration. The second approach has been used of micron-sized mPCL/Col (μmPCL/Col) to increase the fiber-to-fiber distance and, hence, to increase the pore dimension. The third method consists of use of codeposition of μmPCL/Col with heprasil. Heprasil is a synthetic ECM based on chemically modified hyaluronic acid (Cai et al., 2005), which has been developed for 3D cell culture and tissue engineering (Prestwich, 2007). Due to the inclusion of the heprasil (glycosaminoglycan hydrogel) there has been creation of enzymatically degradable matrix pockets within the densely assembled fibers through which cells could migrate. They have found combination of micron-sized fibers with heprasil as most successful method. Besides better cell migration heprasil also promotes the controlled release of bioactive factors for specific tissue engineering applications (Ekaputra et al., 2008). Kidoaki et al. (2005) have also proposed the concept of selective leaching to create microvoids. Similar approach has also been reported with blending of gelatin into PCL electrospinning solution to improve the ability of cell migration into the PCL mesh due to the rapid dissolution of gelatin (Zhang et al., 2005b,c).

There are other methods, which are used by various research groups for improving the cellular infiltration in the 3D electrospun scaffolds. Nam et al. (2007) have used an interesting technique which involves simultaneous mechanical dispersion of NaCl particles and electrospinning of fibers followed by salt leaching. However, this method creates very large pores but they have observed the presence of very dense fiber sheaths in between the created macropores that helps only in surface migration and not into the interior of the fibers. Pham et al. (2006) have used microfibers (around 5–10 μm in diameters) in conjunction with dynamic flow perfusion culture and reported excellent penetration by the cells into an electrospun mesh. They have utilized a multilayering technique to construct a bimodal scaffold consisting of alternating layers of micro- and nanofibers. The inherent advantages of both nanofibers and microfibers may be realized in a single scaffold by using this strategy. In this bilayered scaffold, top layer consists of nanofibers and bottom microfiber layer. This has been used as model system for rat MSC attachment and proliferation. Multilayering electrospinning has also been demonstrated by Kidoaki et al. (2005) in which layered scaffolds are fabricated by electrospinning sequentially different polymers. In another approach, a cellular solution has been electrosprayed concomitantly with electrospinning of poly (ester urethane) urea in such a way that cells become interspersed within the scaffold (Stankus et al., 2006). However, the complexity of the setup used than traditional electrospinning systems limits this approach. Chen et al. (2009) have used a different technique of vacuum seeding to enhance fibroblasts seeding and proliferation at different depths. They have used polycaprolactone electrospun scaffolds. It has been found that kinetics of cell attachment and proliferation are a function of varying vacuum pressure as well as fiber diameter. Recently, Ekaputra et al. (2009) have fabricated poly (ε-caprolactone) (PCL) and its collagen composite blend (PCL/Col) using electrospinning method. They have shown the incorporation of collagen on the surface of the fibers promotes the attachment and proliferation of pig bone marrow mesenchymal cells (pBMMCs). Gui-Bo et al. (2010) have fabricated the nanofibrous composite scaffold of poly L-lactic acid (PLA)/silk fibroin (SF)-gelatin by multilayer electrospinning and have examined the porosity, mechanical properties and biocompatibility *in vitro* and *in vivo*. By using this process scaffolds have achieved the desirable levels of pliability (elastic up to 7.3% strain), the appropriate breaking strength (2.22 MPa) and have been biocompatible. Recent research on electrospun fibers has been on exploring various materials that are electrospinnable, the characterization of the fibers and finding new applications for these fibers (Teo and Ramakrishna, 2006). In this review we have discussed basics of the electrospinning process, spinnable polymers and parameters (solution and processing) that affect the fiber morphology significantly. Finally, we have emphasized the varied applications of the versatile spinning process and its future prospects.

1.1. History of electrospinning

Electrospinning is an old technique. It was first observed in 1897 by Rayleigh, studied in detail by Zeleny (1914) on electrospraying, and patented by Formhals (Formhals, 1934) in 1934. The work of Taylor (1969) on electrically driven jets has laid the groundwork for electrospinning. The term “electrospinning”, derived from “electrostatic spinning”, has been used relatively recently (in around 1994), but its origin can be traced back to more than 60 years ago. From 1934 to 1944, Formhals published a series of patents, describing an experimental setup for the production of polymer filaments using an electrostatic force (Huang et al., 2003). The first patent (US Patent Number: 2116942) on electrospinning was issued for the fabrication of textile yarns and a voltage of 57 kV was used for electrospinning cellulose acetate using acetone and monomethyl ether of ethylene glycol as solvents. This process was patented by Antonin Formhals in 1934 and also later granted related patents (U.S. Patents 2116942, 2160962 and 2187306) in 1938, 1939, and 1940 (Pawlowski et al., 2004). Formhals's spinning process consists of a movable thread collecting device to collect threads in a stretched condition, like that of a spinning drum in conventional spinning (Subbiah et al., 2005). About 50 patents for electrospinning polymer melts and solutions have been filed in the past 60 years (Li and Xia, 2004). Vonnegut and Newbauer (1952) invented a simple apparatus for electrical atomization and produced streams of highly electrified uniform droplets of about 0.1 mm in diameter. After that, Drozin (1955) investigated the dispersion of a series of liquids into aerosols under high electric potentials and Simons (1966) patented an apparatus for the production of non-woven fabrics that were ultra thin and very light in weight with different patterns using electrical spinning. In 1971, Baumgarten (1971) made an apparatus to electrospin acrylic fibers with diameters in the range of 0.05–1.1 μm. Since the 1980s and especially in recent years, electrospinning process has regained more attention probably due to a surging interest in nanotechnology, as ultrafine fibers or fibrous structures of various polymers with diameters down to submicrons or nanometers can be easily fabricated with this process (Huang et al., 2003). The popularity of the electrospinning process can be realized by the fact that over 200 universities and research institutes worldwide are studying various aspects of the electrospinning process and the fiber it produces and also the number of patents for applications based on electrospinning has grown in recent years. Some companies such as eSpin Technologies, NanoTechnics, and KATO Tech are actively engaged in reaping the benefits of the unique advantages offered by electrospinning, while companies such as Donaldson Company and Freudenberg have been using this process for the last two decades in their air filtration products (Ramakrishna et al., 2006).

1.2. Electrospinning process

Electrospinning, a spinning technique, is a unique approach using electrostatic forces to produce fine fibers from polymer solutions or melts and the fibers thus produced have a thinner diameter (from nanometer to micrometer) and a larger surface area than those obtained from conventional spinning processes. Furthermore, a DC voltage in the range of several tens of kVs is necessary to generate the electrospinning. Various techniques such as electrostatic precipitators and pesticide sprayers work similarly to the electrospinning process and this process, mainly based on the principle that strong mutual electrical repulsive forces overcome weaker forces of surface tension in the charged polymer liquid (Chew et al., 2006a). Currently, there are two standard electrospinning setups, vertical and horizontal. With the expansion of this technology, several research groups have developed more sophisticated systems that can fabricate more complex nanofibrous structures in a more controlled and efficient manner (Kidoaki et al., 2005; Stankus et al., 2006). Electrospinning is conducted at room temperature with atmosphere conditions. The typical set up of electrospinning apparatus is shown in Fig. 1 (a and b). Basically, an electrospinning system consists of three major components: a high voltage power supply, a spinneret (e.g., a pipette tip) and a grounded collecting plate (usually a metal screen, plate, or rotating mandrel) and utilizes a high voltage source to inject charge of a certain polarity into a polymer solution or melt, which is then accelerated towards a collector of opposite polarity (Liang et al., 2007; Sill and Recum, 2008). Most of the polymers are dissolved in some solvents before electrospinning, and when it completely dissolves, forms polymer solution. The polymer fluid is then introduced into the capillary tube for electrospinning. However, some polymers may emit unpleasant or even harmful smells, so the processes should be conducted within chambers having a ventilation system (Huang et al., 2003). In the electrospinning process, a polymer solution held by its surface tension at the end of a capillary tube is subjected to an electric field and an electric charge is induced on the liquid surface due to this electric field. When the electric field applied reaches a critical value, the repulsive electrical forces overcome the surface tension forces. Eventually, a charged jet of the solution is ejected from the tip of the Taylor cone and an unstable and a rapid whipping of the jet occurs in the space between the capillary tip and collector which leads to evaporation of the solvent, leaving a polymer behind. (Taylor, 1969; Yarin et al., 2001; Adomaviciute and Milasius, 2007). The jet is only stable at the tip of the spinneret and after that instability starts. Thus, the electrospinning process offers a simplified technique for fiber formation.

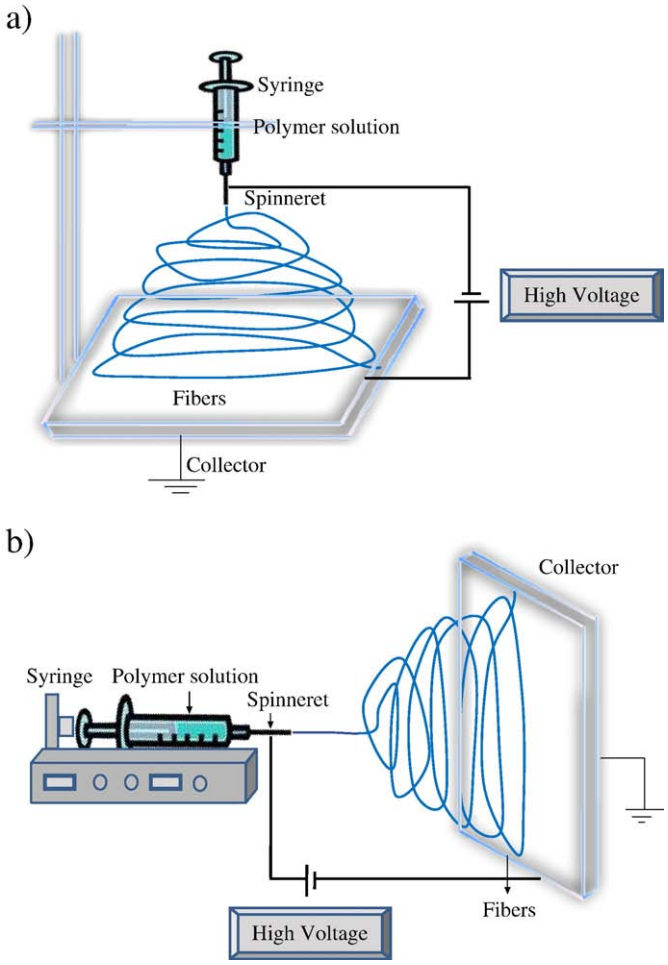

Fig. 1. Schematic diagram of set up of electrospinning apparatus (a) typical vertical set up and (b) horizontal set up of electrospinning apparatus.

2. Polymers used in electrospinning

There are a wide range of polymers that used in electrospinning and are able to form fine nanofibers within the submicron range and used for varied applications. Electrospun nanofibers have been reported as being from various synthetic polymers, natural polymers or a blend of both including proteins (Ohgo et al., 2003; Wnek et al., 2003) nucleic acids (Fang and Reneker, 1997) and even polysaccharides (Son et al., 2004a,b). Over the years, more than 200 polymers have been electrospun successfully from several natural polymers and characterized with respect to their applications (Jiang et al., 2004a). Various polymers used in electrospinning with their characterization methods and applications have been listed in Table 1.

2.1. Natural and synthetic polymers

A variety of polymers are electrospun nowadays and the nanofibers from these electrospun polymer solutions have been used in various applications such as, tissue engineering scaffolds, filtration membranes and in various biomedical applications. Naturally occurring polymers normally exhibit better biocompatibility and low immunogenicity, compared to synthetic polymers, when used in biomedical applications. A strong reason for using natural polymers for electrospinning is their inherent capacity for binding cells since they carry specific protein sequences, such as RGD (arginine/glycine/aspartic acid) (Pierschbacher and Ruoslahti, 1984). In recent years, electrospinning of proteins mainly from collagen, gelatin, elastin and silk fibroin has been reported (Li et al., 2005a, 2006a,b; Zhang et al., 2005a, 2006; Zhong et al., 2006). Typical natural polymers include collagen, chitosan, gelatin, casein, cellulose acetate, silk protein, chitin, fibrinogen etc. Scaffolds fabricated from natural polymers promise better clinical functionality. However, partial denaturation of natural polymers has been reported in recent years that demands concern. Zeugolis et al. (2008) have shown for the first time that the properties of leading natural biomaterial collagen are lost when it is electrospun into nanofibers out of fluoroalcohols such as 1,1,1,3,3,3-hexafluoro-2-propanol or 2,2,2-trifluoroethanol. Collagen is a prominent biopolymer and is used extensively due to its excellent biological and physico-chemical properties for tissue engineering applications. They have also observed the lowering of denaturation temperature and loss of triple helical structure of the collagen with the help of various methods such as SDS PAGE, circular dichorism and thermal analysis. They have found the conversion of collagen into gelatin. Currently, the most widely adopted method for electrospinning of pure collagen or collagen-poly (3-caprolactone) blends involves the use of highly volatile fluoroalcohols such as 1,1,1,3,3,3-hexafluoro-2-propanol (Matthews et al., 2002; Rho et al., 2006; Zhang et al., 2005a; Kwon and Matsuda, 2005) or 2,2,2-trifluoroethanol as solvents (Zhang et al.,

Table 1
Different polymers used in electrospinning, characterization methods and their applications.

Polymers	Applications	Characterizations	References
Poly(glycolide) (PGA)	Nonwoven TE[a] scaffolds	SEM[b], TEM[c], *in vitro* rat cardiac fibroblast culture, *in vivo* rat model	Boland et al. (2004a)
Poly(lactide-co-glycolide)(PLGA)	Biomedical applications, wound healing	SEM, WAXD[d], SAXS[e], degradation analysis	(Zong et al., 2003; Katti et al., 2004)
Poly(ε-caprolactone) (PCL)	Bone tissue engineering	SEM, *in vitro* rat mesenchymal stem cell culture	Yoshimoto et al. (2003)
Poly(l-lactide) (PLLA)	3D cell substrate	SEM, *in vitro* human chondrocyte culture	Fertala et al. (2001)
Polyurethane (PU)	Nonwoven tissue template wound healing	SEM, *in vivo* guinea pig model	Khil et al. (2003)
Poly(ethylene-co-vinyl alcohol) (PEVA)	Nonwoven tissue engineering scaffold	SEM, *in vitro* human aortic smooth muscle cell and dermal fibroblast cultures	Kenawy et al. (2003)
Polystyrene (PS)	Skin tissue engineering	SEM, *in vitro* human fibroblast, keratinocyte, and endothelial single or cocultures	Sun et al. (2005)
Syndiotactic 1,2-polybutadiene	Tissue engineering applications	ESEM[f], XRD[g], FTIR[h]	Hao and Zhang (2007)
Fibrinogen	Wound healing	SEM,TEM,mechanical Evaluation	Wnek et al. (2003)
Poly (vinyl alcohal)/cellulose acetate (PVA/CA)	Biomaterials	SEM, FTIR, WAXD, mechanical evaluation	Ding et al. (2004)
Cellulose acetate	Adsorptive membranes/felts	SEM, FTIR	Zhang et al. (2008b)
Poly(vinyl alcohol)	Wound dressings	SEM, EDX[i]	Jia et al. (2007)
Silk fibroin, silk/PEO[j]	Nanofibrous TE scaffold	SEM, FTIR, XPS[k]	Jin et al. (2002)
Silk	Biomedical Applications	SEM, TEM, WAXD	Zarkoob et al. (2004)
Silk fibroin	Nanofibrous scaffolds for wound healing	SEM, ATR-IR[l], ^{13}C CP/MAS NMR, WAXD, NMR[m], *in vitro* human keratinocyte culture	Min et al. (2004a,b)
Silk/chitosan	Wound dressings	SEM, viscosity analysis, conductivity measurement	Park et al. (2004)
Chitosan/PEO	TE scaffold, drug delivery, wound healing	SEM, XPS, FTIR, DSC[n]	Duan et al. (2004)
Gelatin	Scaffold for wound healing	SEM, mechanical evaluation	Huang et al. (2004)
Hyaluronic acid, (HA)	Medical implant	SEM	Um et al. (2004)
Cellulose	Affinity membrane	SEM, DSC, ATR-FTIR[o]	Ma et al. (2005b)
Gelatin/polyaniline	Tissue engineering scaffolds	SEM, DSC, conductivity measurement, tensile testing	Li et al. (2006a)
Collagen/chitosan	Biomaterials	SEM, FTIR	Chen et al. (2007)

[a] Tissue engineering.
[b] Scanning electron microscopy.
[c] Transmission electron microscopy.
[d] Wide angle X-ray diffraction.
[e] Small angle X-ray scattering.
[f] Environmental scanning electron microscopy.
[g] X-ray diffractometry.
[h] Fourier transform infra red.
[i] Energy dispersive X-ray.
[j] Poly (ethylene oxide).
[k] X-ray photoelectron spectroscopy.
[l] Attenuated total reflectance infra red spectroscopy.
[m] Nuclear magnetic resonance.
[n] Differential scanning calorimeter.
[o] Attenuated total reflectance fourier transform infra red spectroscopy.

2005a; Kwon and Matsuda, 2005; Zhong et al., 2005). Similarly, other research groups have also shown earlier denaturation of native structure and the lowering of denaturation temperature of non-collagenous proteins because of fluoroalcohols (Hong et al., 1999; Cort and Andersen, 1997; Kundu and Kishore, 2004). Recently, it has been shown that 45% of collagen is apparently lost during electrospinning (Yang et al., 2008). Apart from denaturation of natural polymers there is also other problem in fabrication of some natural polymers. Laminin is a component of basement membrane supports cellular attachment, growth, and differentiation *in vitro*. Neal et al. (2008) have fabricated laminin I nanofibers ranging from 90 to 300 nm with beads mesh morphology. They have found that for spinning laminin there is no need of cross-linking agent and the structural features are retained unlike collagen. Synthetic polymers often offer many advantages over natural polymers as they can be tailored to give a wider range of properties such as, necessary mechanical properties (viscoelasticity and strength), and desired degradation rate (Hakkarainen, 2002). Typical synthetic polymers used in biomedical applications are hydrophobic biodegradable polyesters, such as polyglycolide (PGA) (Fang and Reneker, 1997; Boland et al., 2001, 2004a,b), polylactide (PLA) (Bognitzki et al., 2000; Jun et al., 2003; Zeng et al., 2003a; Jing et al., 2003; Yang et al., 2004a,b) and poly (ε-caprolactone) (PCL) (Hsu and Shivkumar, 2004a,b; Ohkawa et al., 2004a; Tan et al., 2005a), which have all been electrospun into nanofibrous scaffolds. Till date, electrospinning has been used for the fabrication of nanofibrous scaffolds from numerous biodegradable polymers, such as poly (ε-caprolactone) (PCL), poly (lactic acid) (PLA), poly (glycolic acid) (PGA), polyurethane (PU), copolymer poly (lactide-co-glycolide) (PLGA), and the copolymer poly (L-lactide-co-ε-caprolactone) [P (LLA-CL)] for bone tissue engineering, cardiac grafts, wound dressings and for engineering of blood vessel substitutes (Li et al., 2002, 2003a; Kim et al., 2003; Yoshimoto et al., 2003; Khil et al., 2003; Bhattarai et al., 2004; Katti et al., 2004; Shin et al., 2004a,b; Mo et al., 2004; Xu et al., 2004,). From the list of various polymers used for electrospinning, we discuss some typical polymers used in electrospinning process.

2.1.1. Silk fibroin

Silk is a well-described natural fiber obtained from silkworms (*Bombyx mori* and *Antheraea mylitta*) and spiders and has been used in textile industries from thousands of years. Basically, silk proteins are of two kinds namely, hydrophobic fibroin and hydrophilic sericin. Silk fibroin protein has been extensively studied as one of the promising materials for biomedical applications, because it has several distinctive biological properties including good biocompatibility, biodegradability, and minimal inflammatory reaction and excellent mechanical properties (Gosline et al., 1986; Altman et al., 2003; Park et al., 2004; Meinel et al., 2005; Dal Pra et al., 2005; Horan et al., 2005). These properties of silk and their potential benefits have

generated an interest in electrospinning silk from various sources including the silkworm cocoon (Zarkoob et al., 1998; Sukigara et al., 2003; Altman et al., 2003), spider (*Nephila clavipes*) dragline silk (Zarkoob et al., 1998), and recombinant hybrid silk-like polymers with fibronectin functionality (Buchko et al., 1999). Silk fibroin (SF) protein can be easily fabricated into nanofibrous form by electrospinning (Min et al., 2004a,b; Jin et al., 2004). With the availability of silk nanofibers, there is now a new set of potential uses that was unattainable before. Initially researchers encountered problems in silk electrospinning experiments because of the selection of appropriate solvents and control of the conformational transitions of fibroin during electrospinning (Cappello et al., 1994). Zarkoob et al. (1998) were the first to report that silk protein fibroin from silkworm *B. mori* cocoons and spider dragline silk from *N. clavipes* silk can be electrospun into nanometer diameter fibers with hexafluoro-2-propanol (HFIP) as a solvent. Afterwards, Sukigara studied the effect of electrospinning parameters (electric field, tip-to-collector distance and concentration) on the morphology and fiber diameter of regenerated silk from *B. mori* using the response surface methodology and found that the silk concentration is the most important parameter in producing uniform cylindrical fibers less than 100 nm in diameter (Sukigara et al., 2003, 2004). Silk nanofibers are used in various fields such as, in biomedical, electrical and textile applications, including tissue-engineered scaffolds, wound dressings and drug delivery systems because of their remarkable properties such as, high specific surface area, increased strength and surface energy and enhanced thermal and electrical conductivity (Huang et al., 2003; Zeng et al., 2003b). Jin et al. have electrospun different blends of poly-(ethylene oxide) (PEO) and silk using aqueous hexaflouro-2-propanol (HFIP) and attained uniform fibers (800–1000 nm) but this technique involved the use of PEO which might have affected the mechanical properties and biocompatibility of fibers (Jin et al., 2002). In order to avoid these problems, researchers have successfully prepared electrospun SF fibers from pure *B. mori* fibroin aqueous solutions (Wang et al., 2006; Alessandrino et al., 2008). Zhang et al. (2008a) have studied the responses of human aortic endothelial (HAEC) and human coronary artery smooth muscle cell (HCASMC) on electrospun silk fibroin scaffolds to enable evaluation of its potential for vascular tissue engineering.

2.1.2. Chitosan

Chitosan is a biocompatible, biodegradable, natural polymer used in biomedical applications and also in cosmetics. Chitosan is an interesting polymer because of its physicochemical properties, including its solid-state structure and the dissolving state conformation (Sakurai et al., 1985; Titoba et al., 1986; Grant et al., 1989; Hasegawa et al., 1992; Pa and Yu, 2001). Electrospun fabrics from pure chitosan were not developed till 2004. Earlier work had been carried out with blends such as poly vinyl alcohol and others. Only after 2004, direct electrospinning of pure chitosan was performed by some researchers using tetrahydrofolate (THF) and acetic acid as a solvent. The non-woven fibers of chitosan with an average diameter down to 130 nm have been generated through electrospinning (Ohkawa et al., 2004b; Geng et al., 2005).

2.1.3. Collagen

Collagen, the most abundant protein family in the body, has been extensively used for *in vitro* and *in vivo* tissue engineering. In many native tissues, polymers of type I and type III collagen are the principal structural elements of the extracellular matrix (Parry and Craig, 1988). There are several different types of collagens, which can be isolated from a variety of sources. More than 80% of collagens in the body are consists of mainly type I, II and III and share similar features in all species. Collagen is highly conserved, relatively non-immunogenic and has been used in a variety of tissue engineering applications (Matthews et al., 2002). The main function of collagen is to provide structural support to the tissue in which it is present, but it is also known to sequester many factors required for tissue maintenance and regeneration. Therefore, it is also considered as "ideal" scaffold material in the tissue engineering field (Pawlowski et al., 2004). The identification of a solvent that suitably dissolves collagen at sufficient concentrations to accomplish electrospinning and the volatility of the solvent for rapid drying of electrospun mats were the key issues for electrospinning of collagen. For the first time electrospinning of collagen was attempted by How et al. (1992) utilizing type I collagen (calf skin) dissolved in HFP and characterization with scanning electron microscopy (SEM) and transmission electron microscopy (TEM) was done. The electrospun collagen scaffolds have been applied for wound dressings and preliminary vascular tissue engineering as it provides an *in vitro* method to create a preformed, nanofibrous collagen scaffold that closely mimics the native collagen network. (Huang et al., 2001a,b; Matthews et al., 2002, 2003; Shields et al., 2004; Boland et al., 2004c; Kidoaki et al., 2005; Telemeco et al., 2005; Li et al., 2005a; Rho et al., 2006). A comparative study of cross-linked and non-cross-linked electrospun scaffolds using glutaraldehyde as the cross-linking agent has been done and it was found that cross-linking increases the diameter of collagen nanofibers as well as the thickness of the scaffolds (Shields et al., 2004).

2.1.4. Hyaluronic acid

Hyaluronic acid (HA), a linear polysaccharide composed of repeating glucuronic acid and N-acetylglucosamine, is the main component of the extracellular matrix (ECM) of connective tissues, and has many important biological functions and is the most commonly used carbohydrate-based natural polymer in tissue engineering (Campoccia et al., 1998; Bulpitt and Aeschlimann, 1999; Shu et al., 2004). HA has been thought to act as a molecular filter, shock absorber, and support structure for collagen fibrils and due to its excellent properties of biocompatibility and biodegradability, it has been used extensively in the biomedical field, for example in wound dressings, tissue scaffolds, arthritis treatment, drug delivery, and components of implant materials (Park et al., 2003; Hokputsa et al., 2003; Yun et al., 2004). Initially, it was difficult to form uniform size fibers from hyaluronan using electrospinning because of the high viscosity, surface tension, and strong water retention ability of the hyaluronan solution. The water retention ability might lead to the fuse of nanofibers electrospun on the collector due to the insufficient evaporation of solvents in electrospinning. The fabrication of HA into nanofibrous nonwoven membranes from aqueous solution was successfully carried out only after the development of blowing-assisted electrospinning (Li et al., 2005a). Um et al. (2004) reported on several approaches to prepare a hyaluronan solution that has sufficient molecular entanglement in a rapidly evaporated solvent, while still maintaining low viscosity and surface tension by using the electroblowing technique. The successful fabrication of HA nanofibers can be mainly attributed to the two new parameters introduced: the rate and the temperature of air blow.

2.1.5. Gelatin

Gelatin is a natural polymer that is derived from collagen by controlled hydrolysis, and is commonly used for pharmaceutical and medical applications because of its biodegradability and biocompatibility in physiological environments (Ikada and Tabata, 1998; Kawai et al., 2000; Kuijpers et al., 2000a,b; Yamamoto et al., 2001; Yao et al., 2004; Balakrishnan and Jayakrishnan, 2005). Generally, gelatin is of two types: Type A and Type B depending on the hydrolysis condition of isolation from collagen. Practical microfibers of gelatin produced via the conventional wet/dry spinning were not common because of the polyelectrolytic nature of gelatin, coupled with its strong hydrogen bonding, hinders its fiber forming capacity (Nagura et al., 2002; Kidoaki et al., 2005; Telemeco et al., 2005; Li et al., 2005a; Zhang et al., 2005a). Apart from these properties, difficulty in dissolving as

colloidal sol at temperatures about or above 37 °C in water and congealing into gels at lower temperatures (e.g., room temperature), gelatin is rarely considered as candidate material for tissue engineering applications without any special treatment (e.g., cross-linking). Electrospinning of gelatin and mechanical characterizations have been done by blending with other polymers in the preparation of tissue engineering scaffolds (Ma et al., 2005a,c).

2.1.6. Fibrinogen

Fibrinogen, nature's provisional wound healing matrix, is another natural polymer of interest for the designing and fabrication of tissue engineering scaffolds as well as hemostatic and wound dressings (Clark et al., 1982; Passaretti et al., 2001; Peretti et al., 2001). Fibrinogen represents a candidate material for use in the development of an electrospun tissue-engineered scaffold because of its innate ability to induce cellular interaction, easy degradability, nonimmunogenic nature, and promote increased cell migration (Underwood et al., 1999, 2001; Ye et al., 2000). Because of the high surface area to volume ratio available for clot formation, electrospun nanofibrous fibrinogen mats are highly suitable for wound dressing and hemostatic products. The electrospun mats of fibrinogen should possess substantial structural integrity, which allow them to be easily removed from the collector and handled. A variety of solvents have been tried for fibrinogen electrospinning. The electrospun fibrinogen mat wets quickly and is also insoluble in normal saline, remains intact as a hydrated mat for at least 48 h and this provides the required characteristics for its applications as hemostatic bandage or tissue engineered scaffolding (Pawlowski et al., 2004).

2.2. Copolymers

Electrospinning with copolymers offers property enhancement of polymeric materials, including tailoring of thermal stability, mechanical strength and barrier properties, and has therefore been often pursued for engineering structural applications through methods as copolymerization, melt-blending and incorporation of inorganic fillers (Wang et al., 2005a). The use of copolymers is a viable scheme to generate new materials of desirable properties and when properly implemented, the performance of electrospun scaffolds based on copolymers can be significantly improved as compared to homopolymers. Biodegradable hydrophobic polyesters generally have good mechanical properties but lack cell affinity for tissue engineering, but with the incorporation of a proper hydrophilic polymer segment, there is increase in the cell affinity. Apart from the cell affinity, the mechanical properties, morphology, structure, pore size and distribution, biodegradability and other physical properties can also be tailored by the use of copolymers in electrospinning. For example, the elastic poly (ethylene-co-vinyl alcohol) (PEVA) nanofibrous mat becomes stiffer after poly (glycolide) (PGA) is added for blend electrospinning (Kenawy et al., 2002). Saito et al. (2001) have synthesized a triblock copolymer containing PLA, p-dioxanone and PEG (PLA-b-DX-b-PEG), unique block copolymer clearly exhibits a good balance between the degradation rate and the hydrophilicity. The thermal stability of poly methyl methacrylate (PMMA) can be improved through copolymerization of methyl methacrylate (MMA) with methacrylic acid (MAA). The glass transition temperature of poly (methacrylic acid) (PMAA) is higher than PMMA and it also exhibits a higher degradation temperature due to formation of anhydride upon heating (Ho et al., 1992; Huang and Chang, 2003). Bhattarai et al. (2003, 2004) have developed a novel block copolymer based on poly (p-dioxanone-co-L-lactide)-block-poly (ethylene glycol) (PPDO/PLLA-b-PEG) that could be electrospun into scaffolds for applications in tissue engineering and drug release and observed that the random disposition of the PPDO and PLLA segments, as well as the incorporation of PEG oligomers, significantly improved the biodegradability and hydrophilicity of the electrospun scaffolds. Electrospun scaffolds based on DegraPol®, a degradable block polyesterurethane, containing crystalline blocks of poly (R)-3-hydroxybutyric acid)-diol and blocks of poly (ε-caprolactone-co-glycolide)-diol linked with a diisocyanate, have been studied as a potential scaffold for skeletal muscle tissue engineering. This block copolymer, DegraPol® has the characteristics of traditional polyesters with good processibility and distinct elasticity of polyurethanes and also exhibited good affinity with tissue cells (Riboldi et al., 2005). Thus, copolymers based electrospinning appears as an attractive option for enhancing the properties of polymers for tissue engineering applications.

3. Effects of various parameters on electrospinning

The electrospinning process is solely governed by many parameters, classified broadly into solution parameters, process parameters, and ambient parameters. Solution parameters include viscosity, conductivity, molecular weight, and surface tension and process parameters include applied electric field, tip to collector distance and feeding or flow rate. Each of these parameters significantly affect the fibers morphology obtained as a result of electrospinning, and by proper manipulation of these parameters we can get nanofibers of desired morphology and diameters (Chong et al., 2007). In addition to these variables, ambient parameters encompass the humidity and temperature of the surroundings which play a significant role in determining the morphology and diameter of electrospun nanofibers (Li and Xia, 2004). In Table 2, we have discussed various parameters and their effects on fiber morphology.

3.1. Solution parameters

3.1.1. Concentration

In the electrospinning process, for fiber formation to occur, a minimum solution concentration is required. It has been found that at low solution concentration, a mixture of beads and fibers is obtained and as the solution concentration increases, the shape of the beads changes from spherical to spindle-like and finally uniform fibers with increased diameters are formed because of the higher viscosity resistance (Deitzel et al., 2001; Liu and Hsieh, 2002; Ryu et al., 2003; McKee et al., 2004; Ki et al., 2005; Haghi and Akbari, 2007). There should be an optimum solution concentration for the electrospinning process, as at low concentrations beads are formed instead of fibers and at high concentrations the formation of continuous fibers are prohibited because of the inability to maintain the flow of the solution at the tip of the needle resulting in the formation of larger fibers (Sukigara et al., 2003). Researchers have attempted to find a relationship between solution concentration and fiber diameter and they found a power law relationship, that increasing the concentration of solution, increases the fiber diameter with gelatin electrospinning (Ki et al., 2005; Jun et al., 2003). Solution surface tension and viscosity also play important roles in determining the range of concentrations from which continuous fibers can be obtained in electrospinning (Deitzel et al., 2001).

3.1.2. Molecular weight

Molecular weight of the polymer has a significant effect on rheological and electrical properties such as viscosity, surface tension, conductivity and dielectric strength (Haghi and Akbari, 2007). This is the other important solution parameter that affects the morphology of electrospun fiber and generally high molecular weight polymer solutions have been used in electrospinning as they provide the desired viscosity for the fiber generation. It has been observed that too low a molecular weight solution tends to form beads rather than fibers and a high molecular weight solution gives fibers with larger average diameters. Molecular weight of the polymer reflects the number of entanglements of polymer chains in a solution, thus solution viscosity. Chain entanglement plays an important role in the

Table 2
Electrospinning parameters (solution, processing and ambient) and their effects on fiber morphology.

Parameters	Effect on fiber morphology	References
Solution parameters		
Viscosity	Low-beads generation, high-increase in fiber diameter , disappearance of beads.	(Jiang et al., 2004a; Huang et al., 2001a; Zhao et al., 2005; Zhang et al., 2005b)
Polymer concentration	Increase in fiber diameter with increase of concentration.	(Kim et al., 2005b; Son et al., 2004c; Jun et al., 2003)
Molecular weight of polymer	Reduction in the number of beads and droplets with increase of molecular weight.	(Chen and Ma, 2004; Demir et al., 2002; Gupta et al., 2005)
Conductivity	Decrease in fiber diameter with increase in conductivity.	(Koski et al., 2004; Jun et al., 2003; Jiang et al., 2004a)
Surface tension	No conclusive link with fiber morphology, high surface tension results in instability of jets.	(Hohman et al., 2001; Zuo et al., 2005; Zhang et al., 2005b; Mit-uppatham et al., 2004)
Processing parameters		
Applied voltage	Decrease in fiber diameter with increase in voltage.	(Demir et al., 2002; Jun et al., 2003; Kim et al., 2005b)
Distance between tip and collector	Generation of beads with too small and too large distance, minimum distance required for uniform fibers.	(Ki et al., 2005; Geng et al., 2005; Buchko et al., 1999; Zhao et al., 2005; Zhang et al., 2005b)
Feed rate/Flow rate	Decrease in fiber diameter with decrease in flow rate, generation of beads with too high flow rate.	(Sill and Recum, 2008; Zuo et al., 2005; Zhang et al., 2005b)
Ambient parameters		
Humidity	High humidity results in circular pores on the fibers.	(Casper et al., 2004; Li and Xia, 2004; Mit-Uppatham et al., 2004)
Temperature	Increase in temperature results in decrease in fiber diameter.	(Reneker and Chun, 1996; Mit-Uppatham et al., 2004)

processing of electrospinning. Hence, even when polymer concentration is low, HM-PLLA (high molecular weight poly-L-lactic acid) can maintain enough number of entanglements of the polymer chains, thus ensuring a sufficient level of solution viscosity to produce a uniform jet during electrospinning and restrain effects of surface tension, which plays a significant role in beads formation on electrospun nanofibers (Tan et al., 2005b). Gupta et al. (2005) have synthesized PMMA varying in molecular weight from 12.47 to 365.7 kDa to investigate the effect of molecular weight of the polymer, and they found that as the molecular weight increased, the number of beads and droplets decreased. It has been observed that high molecular weights are not always essential for the electrospinning process if sufficient intermolecular interactions can provide a substitute for the interchain connectivity obtained through chain entanglements, and using this principle, researchers have prepared oligomer-sized phospholipids from lecithin solutions into nonwoven membranes through electrospinning (McKee et al., 2006; Burger et al., 2006).

3.1.3. Viscosity

Solution viscosity plays an important role in determining the fiber size and morphology during spinning of polymeric fibers. It has been found that with very low viscosity there is no continuous fiber formation and with very high viscosity there is difficulty in the ejection of jets from polymer solution, thus there is a requirement of optimal viscosity for electrospinning. Sukigara et al. (2003) have shown the significant effects of viscosity on silk nanofibers. Earlier, Larrondo and Manley (1981a) also showed that viscosity was important when they electrospun fibers from the melt. The viscosity range of a different polymer solution at which spinning is done is different. Researchers have reported maximum spinning viscosities ranging from 1 to 215 poise (Baumgarten, 1971; Doshi and Reneker, 1995; Deitzel et al., 2002; Buchko et al., 1999). Fong et al. (1999) have studied polyethylene oxide (PEO) to study nanofiber formation in different viscosities, and found that a range of viscosity between 1 and 20 poise is suitable for production of uniform nanofibers by electrospinning. Viscosity, polymer concentration and molecular weight of polymer are correlated to each other. The solution viscosity has been strongly related to the concentration of the solution and the relationship between the polymer viscosity and/or concentration and fibers obtained from electrospinning has been studied in a number of systems, including poly(lactic-co-glycolic acid) (PLGA) (Kim et al., 2005a), poly(ethylene oxide) (PEO) (Huang et al., 2001a; Son et al., 2004c) poly (vinyl alcohol) (PVA) (Ding et al., 2002; Koski et al., 2004; Lee et al., 2004; Zhang et al., 2005b), poly (methyl methacrylate) (PMMA) (Gupta et al., 2005), polystyrene (Jarusuwannapoom et al., 2005), poly (L-lactic acid) (PLLA) (Jun et al., 2003), gelatin (Ki et al., 2005) and dextran (Jiang et al., 2004a). At very high viscosity polymer solutions usually exhibit longer stress relaxation times, which could prevent the fracturing of the ejected jets during electrospinning. An increase in solution viscosity or concentration gives rise to a larger and more uniform fiber diameter (Deitzel et al., 2001). In electrospinning, viscosity of solution plays an important role in determining the range of concentrations from which continuous fibers can be obtained. For solution of low viscosities, surface tension is the dominant factor and just beads or beaded fibers are formed while above a critical concentration, a continuous fibrous structure is obtained and its morphology is affected by the concentration of the solution (Doshi and Reneker, 1995). Taken together, these studies indicate that there exist polymer-specific, optimal viscosity values for electrospinning and this property has a remarkable influence on the morphology of fibers.

3.1.4. Surface tension

Surface tension, more likely to be a function of solvent compositions of the solution plays a critical role in the electrospinning process and by reducing the surface tension of a nanofiber solution; fibers can be obtained without beads. Different solvents may contribute different surface tensions. Generally, the high surface tension of a solution inhibits the electrospinning process because of instability of the jets and the generation of sprayed droplets (Hohman et al., 2001). The formation of droplets, bead and fibers depends on the surface tension of solution and a lower surface tension of the spinning solution helps electrospinning to occur at a lower electric field (Haghi and Akbari, 2007). However, not necessarily a lower surface tension of a solvent will always be more suitable for electrospinning. Basically, surface tension determines the upper and lower boundaries of the electrospinning window if all other variables are held constant (Fong et al., 1999; Zhang et al., 2005b; Pham et al., 2006).

3.1.5. Conductivity/surface charge density

Polymers are mostly conductive, with a few exceptions of dielectric materials, and the charged ions in the polymer solution are highly influential in jet formation. Solution conductivity is mainly determined by the polymer type, solvent used, and the availability of ionisable salts. It has been found that with the increase of electrical conductivity of the solution, there is a significant decrease in the diameter of the electrospun nanofibers whereas with low conductivity of the solution,

there results insufficient elongation of a jet by electrical force to produce uniform fiber, and beads may also be observed. Hayati et al. (1987) have showed that highly conductive solutions are extremely unstable in the presence of strong electric fields, which results in a dramatic bending instability as well as a broad diameter distribution. Generally, electrospun nanofibers with the smallest fiber diameter can be obtained with the highest electrical conductivity and it has been found that the there is drop in the size of the fibers is due to the increased electrical conductivity. It was observed that the jet radius varied inversely with the cube root of the electrical conductivity of the solution (Baumgarten, 1971; Fong et al., 1999; Huang et al., 2001a; Zong et al., 2002a; Jiang et al., 2004a; Mit-Uppatham et al., 2004; Zuo et al., 2005; Kim et al., 2005b; Haghi and Akbari, 2007). Natural polymers are generally polyelectrolytic in nature, for example, gelatin. The ions increase the charge carrying capacity of the jet, thereby subjecting it to higher tension with the applied electric field. Thus the fiber forming ability of the gelatin is less as compared to the synthetic ones. Zong et al. (2002a) have demonstrated the effect of ions by adding ionic salt on the morphology and diameter of electrospun fibers and found that with the addition of ionic salts like KH_2PO_4, NaH_2PO_4, and NaCl it produced beadless fibers with relatively smaller diameters ranging from 200 to 1000 nm. This approach of increasing the solution conductivity by the use of salt addition has also been used for other polymers such as, PEO (Fong et al., 1999), collagen type I-PEO (Huang et al., 2001a), PVA (Zhang et al., 2005b) polyacrylic acid (PAA) (Kim et al., 2005b), polyamide-6 (Mit-Uppatham et al., 2004) and others. With the use of salts, the uniformity of fibers increases and there is a decrease in beads generation.

3.2. Processing parameters

3.2.1. Applied voltage

In the electrospinning process a crucial element is the applied voltage to the solution. Only after attainment of threshold voltage, fiber formation occurs, this induces the necessary charges on the solution along with electric field and initiates the electrospinning process. It has been already proved experimentally that the shape of the initiating drop changes with spinning conditions (voltage, viscosity, and feed rate) (Baumgarten, 1971). There is a little dispute about the behaviour of applied voltage in the electrospinning process. Reneker and Chun (1996) have showed that there is not much effect of electric field on the fiber diameter with electrospinning of polyethylene oxide. Researchers have suggested that when higher voltages are applied, there is more polymer ejection and this facilitates the formation of a larger diameter fiber (Zhang et al., 2005b; Demir et al., 2002). Other authors have reported that an increase in the applied voltage (i.e., by increasing the electric field strength), increases the electrostatic repulsive force on the fluid jet which ultimately favours the narrowing of fiber diameter. In most cases, a higher voltage causes greater stretching of the solution due to the greater columbic forces in the jet as well as a stronger electric field and these effects lead to reduction in the fiber diameter and also rapid evaporation of solvent from the fibers results. At a higher voltage there is also greater probability of beads formation (Buchko et al., 1999; Deitzel et al., 2001; Demir et al., 2002; Megelski et al., 2002; Lee et al., 2004; Mo et al., 2004; Katti et al., 2004; Pawlowski et al., 2004; Haghi and Akbari, 2007). Similar behaviour of applied voltage on fiber diameter is also observed by Larrondo and Manley (1981a,b,c). They have showed the decrease of fiber diameter by roughly half by doubling the applied electric field. Thus, voltage influences fiber diameter, but the level of significance varies with the polymer solution concentration and on the distance between the tip and the collector (Yordem et al., 2008).

3.2.2. Feed rate/Flow rate

The flow rate of the polymer from the syringe is an important process parameter as it influences the jet velocity and the material transfer rate. A lower feed rate is more desirable as the solvent will get enough time for evaporation (Yuan et al., 2004). There should always be a minimum flow rate of the spinning solution. It has been observed that the fiber diameter and the pore diameter increases with an increase in the polymer flow rate in the case of polystyrene (PS) fibers and by changing the flow rate, the morphological structure can be slightly changed. Few studies have systematically investigated the relationship between solution feed or flow rate on fiber morphology and size (Megelski et al., 2002; Zong et al., 2002a). High flow rates result in beaded fibers due to unavailability of proper drying time prior to reaching the collector (Wannatong et al., 2004; Yuan et al., 2004; Kim et al., 2005a; Zuo et al., 2005).

3.2.3. Types of collectors

One important aspect of the electrospinning process is the type of collector used. In this process, a collector serves as a conductive substrate where the nanofibers are collected. Generally, aluminium foil is used as a collector but due to difficulty in transferring of collected fibers and with the need for aligned fibers for various applications, other collectors such as, conductive paper, conductive cloth, wire mesh (Wang et al., 2005b), pin (Sundaray et al., 2004), parallel or grided bar (Li et al., 2004), rotating rod, rotating wheel (Xu et al., 2004), liquid non solvent such as methanol coagulation bath (Ki et al., 2007) and others are also common types of collectors nowadays. In the blowing-assisted electrospinning of hyaluronic acid, Wang et al. (2005b) used two kinds of collector aluminium foil and wire screen and found that a less conductive area of wire screen imposes a negative effect on fiber collection. With less conductive area, there was generation of beaded fibers because of the less surface area. In another study they compared wire screen with aluminium foil and wire screen without aluminium foil in the same conductive area and found that pure wire screen is a better collector for fiber collection because with the use of wire screen the transfer of fibers to other substrates became easy. The fiber alignment is determined by the type of the target/collector and its rotation speed (Kumbar et al., 2008). The generated nanofibers are deposited on the collector as a random mass due to the bending instability of the highly charged jet (Reneker et al., 2000; Shin et al., 2001a). Several research groups have demonstrated the use of a rotating drum or a rotating wheel-like bobbin or metal frame as the collector, for getting aligned electrospun fibers more or less parallel to each other (Doshi and Reneker, 1995; Deitzel et al., 2001; Fong et al., 2002). Several types of split electrodes have been used for getting aligned nanofibers and typically such collectors consist of two conductive substrates separated by a void gap where aligned nanofibers are deposited (Li et al., 2003b, 2004, 2005b; Jalili et al., 2006).

3.2.4. Tip to collector distance

The distance between the tip and the collector has been examined as another approach to control the fiber diameters and morphology. It has been found that a minimum distance is required to give the fibers sufficient time to dry before reaching the collector, otherwise with distances that are either too close or too far, beads have been observed (Lee et al., 2004; Geng et al., 2005; Ki et al., 2005). The effect of tip and the collector distance on fiber morphology is not as significant as other parameters and this has been observed with electrospinning of PVA (Zhang et al., 2005b), gelatin (Ki et al., 2005), chitosan (Geng et al., 2005) and poly (vinylidene fluoride) (Zhao et al., 2005). It has been reported that flatter fibers can be produced at closer distances but with increase in distance rounder fibers have been observed with the spinning of silk-like polymer with fibronectin functionality (Buchko et al., 1999). For polysulfone, closer distances between the tip and collector has yielded smaller fibers (Pham et al., 2006). One important physical aspect of the electrospinning nanofibers is their dryness from the solvent used to dissolve the polymer (Jalili et al., 2005). Thus, there

should be optimum distance between the tip and collector which favours the evaporation of solvent from the nanofibers.

3.3. Ambient parameters

Apart from solution and processing parameters, there are also ambient parameters that include humidity, temperature etc. Studies have been conducted to examine the effects of ambient parameters (i.e., temperature and humidity) on the electrospinning process. Mit-Uppatham et al. (2004) have investigated the effect of temperature on the electrospinning of polyamide-6 fibers ranging from 25 to 60 °C and found that with increase in temperature, there is a yield of fibers with decreased fiber diameter, and they attributed this decline in diameter to the decrease in the viscosity of the polymer solutions at increased temperatures. There is an inverse relationship between viscosity and temperature. The variation in humidity while spinning polystyrene solutions has been studied and shows that by increasing humidity there is an appearance of small circular pores on the surface of the fibers; further increasing the humidity leads to the pores coalescing (Casper et al., 2004). It has been found that at very low humidity, a volatile solvent may dry rapidly as the evaporation of the solvent is faster. Sometimes the evaporation rate is so fast than compared to the removal of the solvent from the tip of the needle and this would create a problem with electrospinning. As a result, the electrospinning process may only be carried out for a few minutes before the needle tip is clogged (Baumgarten, 1971). It has also been suggested that the high humidity can help the discharge of the electrospun fibers (Li and Xia, 2004; Li et al., 2005a). Hence, apart from solution and processing parameters, ambient parameters also affect the electrospinning process.

4. Solvents used for electrospinning

The solvent used in preparing polymer solutions has a significant influence on its spinnability, because the first and foremost step in the electrospinning process is dissolution of polymer in a suitable solvent. Solvents should have some properties such as, good volatility, vapour pressure, boiling point and should maintain the integrity of the polymer solution. Thus for successful electrospinning the selection of an appropriate solvent system is indispensable. The intermolecular interaction in a polymer–solvent system (binary system) is either attractive or repulsive which depends solely on the type of solvent (Zhang et al., 2002). In electrospinning, rapid solvent evaporation and phase separation occurs due to jet thinning, solvent vapour pressure plays a critical role in determining the evaporation rate and the drying time. Solvent volatility also plays a significant role in the formation of nanostructures as it influences the phase separation process. Various research groups have investigated the effect of solvents namely, chloroform, ethanol, dimethylformamide (DMF), mixture of trifluoroacetic acid and dichloromethane and water for electrospinning of poly (ethylene oxide) (PEO), polystyrene and poly (ethylene terephthalate) and showed the effect of solvent properties and polymer concentration on the morphology, structure, and mechanical and thermal properties while electrospinning (Son et al., 2004b; Wannatong et al., 2004; Veleirinho et al., 2008). It is well known that the morphology and size of electrospun nanofibers strongly depend on solution properties such as, viscosity and surface tension. Different solvents may contribute different surface tensions. The solution viscosity is determined by the concentration of the polymer, but the value of surface tension depends on both the polymer and solvent (Reneker and Chun, 1996; Yang et al., 2004c). Doshi and Reneker (1995) have pointed out that by reducing the surface tension of a polymer solution, fibers could be obtained without beads, but this should be applied with caution. It has been recognized that surface tension seems more likely to be a function of solvent compositions, but is negligibly dependent on the polymer concentration. A lower surface tension of the solvent is not always necessarily suitable for electrospinning (Fong and Reneker, 1999; Liu and Hsieh, 2002). The properties of solvents have a profound effect on fiber diameter. In Table 3, we have shown different properties of solvents such as surface tension, dielectric constant and boiling point that should be kept in mind during selection for electrospinning process. Basically, a solvent performs two crucial roles in electrospinning: firstly to dissolve the polymer molecules for forming the electrified jet and secondly to carry the dissolved polymer molecules towards the collector (Ohkawa et al., 2004a). A list of typical solvents used in the electrospinning process has been described in Table 4 with the average fiber diameters of produced nanofibers. The solvents used in electrospinning of polymers can provide very useful information for understanding the effects of solution properties such as conductivity. Dimethylformamide (DMF), a dipolar aprotic solvent, which has a high dielectric constant and dipole moment, has been successfully used as a solvent for electrospinning of poly (acrylonitrile) and polyurethane urea copolymer and biodegradable poly (*p*-dioxanone-*co*-L-lactide)-block poly (ethylene glycol) copolymer electrospinning and its addition enhances the solution conductivity which is a prerequisite for the formation of bead free uniform fibers (Buchko et al., 1999; Demir et al., 2002; Lee et al., 2002a, 2003a; Bhattarai et al., 2004). The effect of varying concentrations of solvents, acetic acid has been observed for chitosan electrospinning, and it was found that by increasing the concentration of solvent, there was a gradual decrease in surface tension of the solution which favoured production of thinner fibers (Geng et al., 2005).

Table 3
Properties of different solvents used in electrospinning process.

Solvents	Surface tension (mN/m)	Dielectric constant	Boiling point (°C)	Density (g/ml)
Chloroform	26.5	4.8	61.6	1.498
Dimethyl formamide	37.1	38.3	153	0.994
Hexafluoro isopropanol	16.1	16.70	58.2	1.596
Tetrahydrofuran				
Trifluoro ethanol	26.4	7.5	66	0.886
Acetone	21.1	27	78	1.393
Water	25.20	21	56.1	0.786
Methanol	72.8	80	100	1.000
Acetic acid	22.3	33	64.5	0.791
Formic acid	26.9	6.2	118.1	1.049
Dichloro methane	37	58	100	1.21
Ethanol	27.2	9.1	40	1.326
Tri fluoro acetic acid	21.9	24	78.3	0.789
	13.5	8.4	72.4	1.525

5. Melt electrospinning

The most remarkable advantage of electrospinning is that it can be performed with various polymers both in solution and in the melt (Demir et al., 2002). Melt electrospinning allows new approaches to various applications, overcoming technical restrictions governed by solvent accumulation and toxicity (Dalton et al., 2006a). In melt electrospinning, instead of a solution, the polymer melt is introduced into the capillary tube and has to be performed in a vacuum condition and for that the capillary tube, the traveling of the charged melt fluid jet, and the metal collecting screen must be encapsulated within a vacuum (Larrondo and Manley, 1981a,b,c). Some chemicals that are used as solvents for dissolving the polymers being electrospun may leave remnants that are not scientifically compatible. Therefore, in spite of the many potential applications, environmental and health limitations, as well as productivity complications do exist with solvent based electrospinning systems. Many solvents that are used in electrospinning are often costly and this is a major part of the cost factor associated with the process. Thus, there is a persistent desire to

Table 4
Different solvents used in electrospinning.

Polymers	Solvents	Fiber diameter (nm)	Applications	References
Silk fibroin/PEO	Water	590 ± 60	Bone tissue engineering	Li et al. (2006b)
Gelatin	Acetic/Formic acid	109–761	Biomaterial scaffold	Songchotikunpan et al. (2008)
Collagen type I	HFP[a]	100–600	Materials science and engineering	Yang et al. (2008)
Collagen type II	HFP	496	Cartilage engineering	Shields et al. (2004)
Gelatin/PVA	Formic acid	133–447	Controlled release of drugs	Yang et al. (2007)
Chitosan	Acetic acid	130	Biomedical applications	Geng et al. (2005)
PVA	Water	250–300	Drug delivery	Zeng et al. (2005)
Chitosan/PVA	Formic acid , TFA[b], HCl	330	Tissue engineering	Ohkawa et al. (2004a)
Cellulose acetate	Acetone, DMF[c], Trifluoroethylene (3:1:1)	200–1000	Filtration	Ma et al. (2005b)
HA/Gelatin	DMF/Water	190–500	Tissue engineering	Li et al. (2006a)
Fibrinogen	HFP	80 ± 30	Wound repair	Wnek et al. (2003)
Polyamide-6	m-Cresol + Formic acid	98.3 ± 8.2	Biomedical applications	Mit-uppatham et al. (2004)
Polyurathane	Water	100–500	Tissue engineering	Pedicini and Farris (2003)
Polycaprolactone	DMF + Methylene chloride	200	Wound healing	Lee et al. (2003b)
Collagen/chitosan	HFP/TFA	300–500	Biomaterial scaffolds	Chen et al., 2007
Chitin	HFP	163	Wound healing	Noh et al. (2006)
PCL/Gelatin	TFE[d]	470 ± 120	Wound healing	Chong et al. (2007)
Polyaniline/Gelatin	HFP	61 ± 13	Tissue engineering	Li et al. (2006c)

[a] Hexafluoro isopropanol.
[b] Trifluoro acetic acid.
[c] Dimethyl formamide.
[d] Trifluoro ethylene.

produce fibers using alternative methods, with the intent of cleaner processing, environmental safety, and productivity. Although, a vast majority of the fibrous structures are being generated by solvent based electrospinning, melt electrospinning can offer several advantages over solution electrospinning such as, no requirement of dissolution of polymers in organic solvents and their removal/recycling, environmentally safe and a higher throughput with no loss in mass by solvent evaporation, and generation of sub-micron scale fibers of polymers which lack appropriate solvents at room temperature (for example polyethylene and polypropylene) (Zhou et al., 2006; Zhmayev et al., 2008). Therefore, there is great interest towards the use of molten polymers to produce electrospun mats as these are also less expensive. Regardless of the potential benefits of melt-electrospinning, very little progress has been made in the past 20 years. Larrondo and Manley (1981a,b,c) have electrospun a molten polypropylene (melt flow indexes 0.5–2.0) with an electric field strength of 3–8 kV cm^{-1} and spinning distance of 1–3 cm more than two decades ago, for the first time and succeeded in making fibers of diameters greater than 50 μm. Owing to large increase in viscosity that could be many orders of magnitude greater than that of a polymer solution they were unable to spin submicrometer diameter fibers. Giza et al. (2000) have examined the high speed, melt-spinning of nylon 6 nanocomposites with birefringence, and found greater orientation (birefringence) of the nanocomposite fibers at lower take-up speeds (1–3 km/h) than neat one and vice-versa at higher take-up speeds (>4 km/h). Other research groups (Kim and Lee, 2000; Chun et al., 1999), and the University of Massachusetts at Dartmouth, have conducted research on melt-electrospinning polymers including poly (ethylene terephthalate) and polyethylene, and reported generation of fibers in a wide range of diameters. Melt electrospinning is a feasible approach for direct *in vitro* electrospinning, and biodegradable polymers can form high quality electrospun fibers with good diameters and excellent uniformity (Dalton et al., 2006b). The parameters that govern melt electrospinning are very different from those of solution electrospinning such as, much lower spinneret flow rates, and the very large viscosity of the polymer often magnitudes greater for melt electrospinning systems (Larrondo and Manley, 1981a,b,c; Kim and Lee, 2000; Lyons et al., 2004) The flow rates required for melt electrospinning to obtain high quality electrospun fibers are 0.1 mL/h or lower, which is significantly lower than for solution electrospinning, in which flow rates such as 5 mL/h are used (Matthews et al., 2002). At present, despite offering various advantages over solution electrospinning, melt electrospinning is still in its infancy due to high viscosity, very high processing temperature and its inability to attain fibers in nanometer range. These higher temperatures may preclude their being used for tissue engineering or drug delivery applications. In Table 5, there is listing of some typical polymers that can be spun in the melt form, with their processing temperatures. Complete understandings of this process, and its potential to replace solution electrospinning, have not yet been realized entirely.

6. Characterizations of electrospun nanofibers

The characterization of fibers produced by the electrospinning process remains one of the most difficult tasks as the chances of getting single fibers are rare. In order to empirically understand electrospinning process, assessment of the entire process from polymer selection to mechanical testing needs to be carried out accurately. Generally in electrospinning, the polymers used are characterized into three distinct categories: physical and structural, mechanical, and chemical (Lyons and Ko, 2005). Presently, nanofibers have attracted the attention of researchers due to their remarkable micro and nano structural characteristics, high surface area, small pore size, and the possibility of their producing three dimensional structures that enable the development of advanced materials with sophisticated applications. To understand the characteristics of the structure and morphology of nanofibers as a function of process parameters, material characters and also the different electrospinning processes various studies have been conducted by different research

Table 5
Different polymers being used for electrospinning in melt form.

Polymer	Processing temperature (°C)	References
Polypropylene	220–240	Larrondo and Manley (1981a,b,c)
Poly(ethylene terephthalate)	270	Lyons et al. (2004)
Poly-(ethylene glycol-block-ε-caprolactone	58.2	Dalton et al. (2006a)
Polyethylene	200–220	Larrondo and Manley (1981ab)
Poly(methyl methacrylate)	130–157	Larrondo and Manley (1981c)
Polyamides (nylon)	220	Wente (1956)
Polystyrene	240	(Larrondo and Manley, 1981b; Wente, 1956)

groups (Moses et al., 2001; Shin et al., 2001a,b; Reneker et al., 2000; Fridrikh et al., 2003; Subbiah et al., 2005).

6.1. Geometrical characterizations

Physical characterization is associated with structure and morphology of the sample and the nanofibers internal structure basically determines the physical and mechanical properties. Geometric properties of nanofibers include fiber diameter, diameter distribution, fiber orientation, and fiber morphology (e.g. cross-section shape and surface roughness). For the characterization of geometric properties, techniques such as scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) are used (Srinivasan and Reneker, 1995; Demir et al., 2002; Li et al., 2002, 2006a; Megelski et al., 2002; Ayutsede et al., 2005; Park et al., 2006). SEM is used been used by many researchers to observe the morphology of the fibers produced, (Doshi and Reneker, 1995; Srinivasan and Reneker, 1995; Reneker and Chun, 1996; Fong and Reneker, 1999; Demir et al., 2002; Fong et al., 2002) as SEM is capable of detecting fiber diameters and morphologies, but the resolution is less at extreme magnifications. Fig. 2 shows the typical SEM image of polymeric electrospun fibers. For SEM, there is a requirement for the samples to be electrically conductive, therefore, for most of the electrospun polymers produced, a gold or platinum coating must be applied that may alter the diameter readings at higher magnifications. Nevertheless, SEM remains a quick method for observing the fibers produced and it requires a very small sample size for its operation. Transmission electron microscopy (TEM) is another alternative for obtaining fiber diameters for extremely small fibers (<300 nm). Atomic force microscopy (AFM) is yet another implementation, used to determine fiber diameter but the process of obtaining an accurate measurement becomes more difficult due to tip convolution. However, AFM remains the best instrument to observe any type of surface morphology and exact descriptions of the fiber surface. For a precise measurement, two fibers crossing each other on the surface are generally chosen (Srinivasan and Reneker, 1995; Kim and Reneker, 1999). Doshi and Reneker (1995) have used a laser light diffraction method to observe the decrease in diameter on the jet until the jet diameter became smaller than the frequency of visible light. To obtain information regarding the crystallinity of the sample, other forms of characterization must be used such as polarized light microscopy which is perhaps the easiest method and determination is done by the amount of birefringence produced (Srinivasan and Reneker, 1995; Norris et al., 2000). Polarized light microscopy is a very cost-effective and quick test that can be performed on the collected fibers. Various research groups (Larrondo and Manley, 1981a,b,c; Srinivasan and Reneker, 1995; Buchko et al., 1999; Fong and Reneker, 1999; Norris et al., 2000; Wang et al., 2003; Zong et al., 2003) have used many of the alternative methods to determine the crystallinity of the produced nanofibers with varying levels of success and these methods need a reference of known crystallinity to measure against. These methods include X-ray diffraction, both wide angle and small angle (WAXS and SAXS) and differential scanning calorimetry (DSC). Some techniques such as X-ray photoelectron spectroscopy (XPS), contact angle measurements and Attenuated total reflectance Fourier transform infra red spectroscopy (ATR-FTIR) are also being used to determine the surface chemistry of the electrospun nanofibers.

Porosity is another geometric parameter and the porosity and pore size of nanofiber membranes are important for its applications in filtration, template for tissue engineering, protective clothing, etc. (Li et al., 2002; Schreuder-Gibson et al., 2002; Zussman et al., 2002). The pore size measurement can be conducted by a capillary flow porometer, mercury porosimetry and researchers have reported highly porous structure of electrospun nanofibrous scaffolds with 91.63% porosity, a total pore volume of 9.69 mL/g, a total pore area of 23.54 m^2/g, and a pore diameter ranging broadly from 2 to 465 μm with the utilization of these methods (Stillwell, 1996; Li et al., 2002; Schreuder-Gibson et al., 2002). With electrospun fibers there is always a problem of small pore size which is not very suitable for the cellular infiltration /migration. In order to overcome this problem Lee et al. (2005a) have used modified approach by combining electrospinning technology and salt leaching/gas foaming methods for the fabrication of an electrospun fibrous scaffold with dual-sized pores that results in intrinsic pores formed between nanofibers and also micro-sized pores created by salt particles that are distributed in the scaffolds.

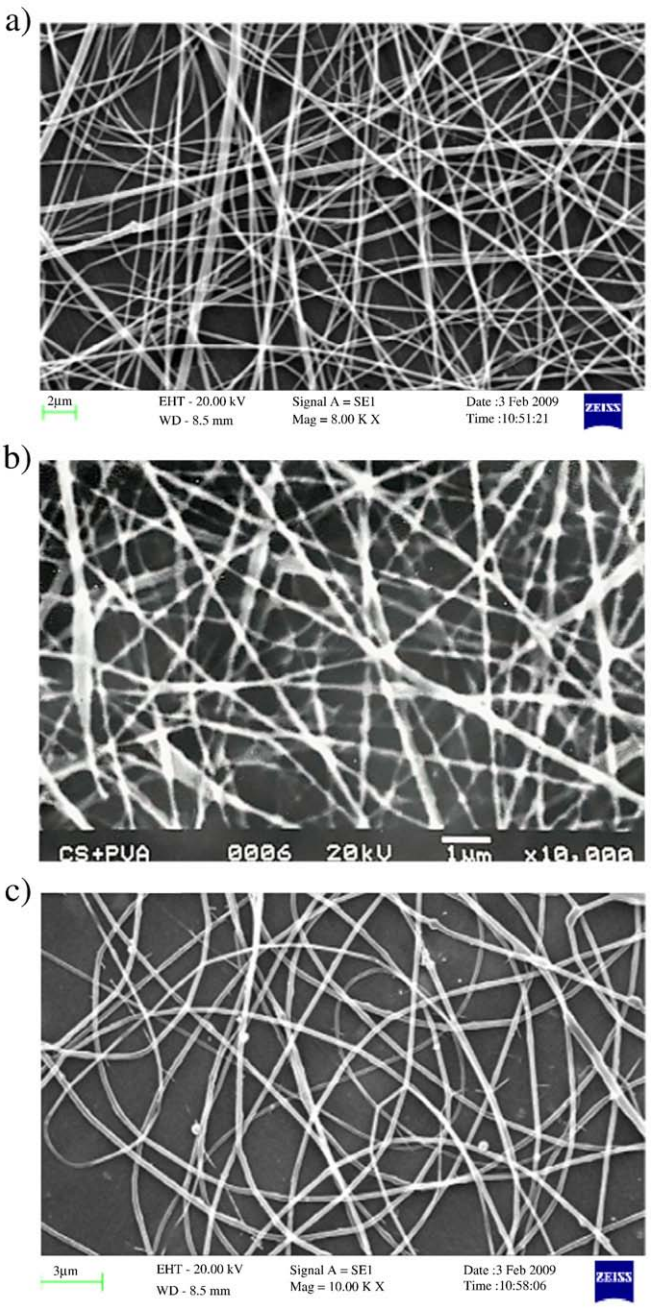

Fig. 2. SEM images of polymeric electrospun fibers (magnification 8000× and 10,000× respectively). (a) Nanofibers of 4% poly ethylene oxide solution at 15 kV voltage (average fiber diameter 250 ± 50 nm). (b) Chitosan/poly vinyl alcohol (2% chitosan and 9% PVA in 50:50 ratios) fibers at 17 kV voltage (average fiber diameter 200 ± 32 nm). (c) Silk fibroin (6%) from non-mulberry tropical tasar silkworm, *Antheraea mylitta* electrospun fibers at 15 kV (average fiber diameter 240 ± 60 nm).

6.2. Chemical characterizations

The characterization of the molecular structure of a nanofiber can be done by Fourier transform infra red (FTIR) and nuclear magnetic resonance (NMR) techniques (How, 1985; Huang et al., 2000). If we blend two polymers together for the fabrication of nanofibers, not only can the structure of the two materials be detected but the intermolecular interaction can be determined by the use of these methods. The presence of an ordered secondary structure 3_{10}-helix for silk fibroin dissolved in HFIP, has been confirmed from the high-resolution solution ^{13}C-NMR and circular dichorism (CD) studies (Zhao et al., 2003). The NMR spectrum in the case of a collagen and PEO blend used for electrospinning of nanofibers, showed a new phase structure which was caused by the hydrogen bond formation between the ether oxygen of PEO and the protons of the amino and hydroxyl groups in collagen (Huang et al., 2001a). Super molecular structure relates the configuration of the macromolecules in a nanofiber, characterized by optical birefringence, wide angle X-ray diffraction (WAXD), small angle X-ray scattering (SAXS) and differential scanning calorimeter (DSC) (Buchko et al., 1999; Chun et al., 1999; Chen et al., 2001; Zussman et al., 2002). Fong and Reneker (1999) have studied the birefringence of the styrene–butadiene–styrene (SBS) triblock copolymer nanofibers with diameters around 100 nm under an optical microscope and the occurrence of birefringence reflects the molecular orientation. Surface chemical properties of nanofibers can be evaluated by its hydrophilicity, which can be measured by the water contact angle analysis of the nanofiber membrane surface and can also be determined XPS, and ATR-FTIR (Deitzel et al., 2002; Huang et al., 2003). Researchers have used Raman Spectroscopy and Fourier Transform Infrared Spectroscopy for the changes that may be taking place at the molecular level (Wang et al., 2003; Pedicini and Farris, 2003).

6.3. Mechanical characterizations

Precise measurement of mechanical properties of the nanofibrous matrix is crucial, especially for biomedical applications, for example as scaffolds, because the scaffold must be able to withstand the forces exerted by growing tissue or during physiological activities and related biomechanics, e.g., pulsed blood flow (Chew et al., 2006b). Mechanical characterization is achieved by applying tensile test loads to specimens prepared from the electrospun ultra fine non-woven fiber mats. During mechanical characterization of single nanofibers sufficient care must be taken in sample mounting in order to avoid severe damage or sample manipulation (Huang et al., 2004). A variety of approaches has been applied towards mechanical characterization of nanofibers and nanowires by employing nanoindentation, bending tests, resonance frequency measurements, and microscale tension tests. Many authors reported that there is no anisotropy in the in-plane tensile behaviour when the nanofibrous membranes are collected on a static collector screen but Lee et al. (2002a,b) have found that the electrospun nonwoven mats had different properties in different directions when the membranes were obtained from a rotating drum as the fiber orientation depends on the linear velocity of the drum surface and other electrospinning parameters. Young's modulus, tensile strength, and the strain at break are also determined by performing tensile tests with single polymer fibers. A commercial nano tensile testing system (Nano Bionix System, MTS, TN, USA) is being used to conduct the tensile test for the evaluation of mechanical properties of single ultrafine polymeric fibers of Polycaprolactone (PCL) (Tan et al., 2005a). Inai et al. (2005) have also carried out tensile tests of single electrospun poly (L-lactic acid) (PLLA) nanofibers collected from a rotating disc at different collection speeds. The tensile strength of various polymers has been listed in Table 6. Tension tests for determining mechanical strength of electrospun nanofibers simply follows the macroscale standards and involves the least number of assumptions necessary to extract material properties. This method is useful for fibers with diameters approaching towards 1 μm and allows for fiber testing until failure (Haque and Saif, 2003). Chew et al. (2006b) have conducted tensile tests on single electrospun nanofibers and fibers were mounted onto a cardboard mount with double-sided tape. The gauge length of the fiber specimen was set at 20 mm.

Table 6
Mechanical strength of some of the typical electrospun fibers.

Polymers	Ultimate strength	Reference
Collagen II	3.3 ± 0.3 MPa	Shields et al. (2004)
poly(ε-caprolactone)	40 ± 10 MPa	Tan et al. (2005a)
Gelatin	4.79 MPa	Huang et al. (2004)
Cross-linked gelatin	12.62 ± 1.28 MPa	Zhang et al. (2006)
Silk fibroin	7.25 MPa	Ayutsede et al. (2005)
Poly(vinylchloride)/Polyurethane (25/75)	6.30 MPa	Lee et al. (2003c)
Polyethylene oxide	10 ± 0.2 MPa	Ojha et al. (2008)

The elastic properties of electrospun membranes are determined by another instrument that is AFM, which consists of a cantilever and tip assembly that is used for scanning of the surface. By measuring the deflection of the cantilever due to the repulsion of contacting atomic shells of the tip and the sample atomic resolution can be obtained with very slight contact (DiNardo, 1994). AFM Phase Imaging is an extension of tapping mode which allows detection of variations in composition and hardness (Ramanathan et al., 2005). The bending moduli and shear moduli of the electrospun collagen fibers have been determined by AFM by performing micromechanical bending tests with native and glutaraldehyde cross-linked single electrospun fibers (Yang et al., 2008). Cuenot et al. (2000, 2003) have used resonant contact AFM approaches for measuring the elastic modulus of the nanofibers. In this testing method, there is a requirement of nanofibers attachment to a cantilever tip (Yuya et al., 2007). AFM-based nanoindentation method has been used to measure the elastic moduli of one-dimensional nanostructures such as nanowires and electrospun nanofibers. Although this method has been used successfully for mechanical characterization, there are certain limitations too, such as uncertainties stemming from the nanoindenter tip shape and the relative tip fiber configuration, the effect of fiber surface curvature and roughness, and the adhesion force between the sample and the indenter (Ko et al., 2003; Tan and Lim, 2006). In an indentation experiment, the indenter and the sample, both with a characteristic stiffness, are arranged in series and the indenter consists of a silicon AFM tip, which is much stiffer than the biological sample (Wenger et al., 2007).

Research groups have also employed a three-point nanoscale bending test with an AFM tip to determine the elastic modulus of nanofibers and found an increase in the elastic modulus with the decrease in the fiber diameter. This size-dependent behaviour was due to shearing of fibrils within the nanofibers to the total deflection of the nanofibers and transformation of the mechanical properties due to the orientation of polymer molecules inside nanofibers arising from the strong strain forces in polymer jets (Shin et al., 2006; Sun et al., 2008). Yuya et al. (2007) have well described a microcantilever-based, vibrational method for determining Young's modulus of a single electrospun nanofiber. This technique basically relies on the conventional beam dynamics for which an analytical relation between fiber stiffness and the resonant frequencies is obtained for specific geometries. This method of mechanical strength determination is mostly used with metallic nanofibers but not very common with polymeric fibers because of the limited bending rigidity of the fibers that results in a whipping motion under lateral excitation (Naraghi et al., 2007).

7. Applications

Recently, researchers have begun to look into various applications of electrospun fibers and mats as these provide several advantages

such as high surface to volume ratio, very high porosity and enhanced physico-mechanical properties as in this process, manipulation of the solution and process parameters can be easily done to get the desired fiber morphology and mechanical strength. In addition to these, the electrospun fibers are required in a small amount and the electrospinning process itself is a versatile process as fibers can be spun into any shape using a wide range of polymers (Doshi and Reneker, 1995; Kim and Reneker, 1999). Electrospun nanofibers are broadly applied in biomedical applications, as tissue engineering scaffolds, in wound healing, drug delivery, filtration, as affinity membrane, in immobilization of enzymes, small diameter vascular graft implants, healthcare, biotechnology, environmental engineering, defense and security, and energy storage and generation and in various researches that are ongoing (How, 1985; Reneker et al., 2000; Stitzel et al., 2001; Smith and Ma, 2004; Ramakrishna et al., 2006). Since the early 1980's, electrospun polymer nanofibers have already been proposed for vascular and breast prostheses applications. A number of US patents have been issued on fabrication methods and techniques for these prostheses such as, covering vascular prostheses include 4044404, 4552707, 4689186, 4878908, 4965110, and 5866217 (Martin et al., 1977, 1985; How, 1985; Bornat, 1987; Berry, 1990; Stenoien et al., 1999) and for breast prosthesis has been disclosed in a US patent 5376117 (Pinchuk et al., 1994). Reviewing the number of patents, we can see that approximately two-thirds of all electrospinning applications are in the medical field. Of the remaining patents, one-half deals with filtration applications, and all other applications share the remaining half (Burger et al., 2006). Owing to application of these nanofibers in diverse fields, various research and developments are going in the fields of electrospinning. A schematic diagram of electrospinning applications in various fields is shown in Fig. 3.

7.1. Tissue engineering applications

Tissue engineering is a multidisciplinary field that combines both the principles of engineering and life sciences for the development of biological substitutes and also for restoration, maintenance, or improvement of tissue function. Biomaterials research is an emerging field which plays a pivotal role in tissue engineering by serving as matrices for cellular in growth, proliferation, and new tissue formation in three-dimensions (Langer and Vacanti, 1993; Nerem and Sambanis, 1995; Hubbell, 1995). When compared to other fiber forming processes such as self-assembly and phase separation techniques, electrospinning provides a simpler and more cost-effective means to produce fibrous scaffolds with an inter-connected pore structure and fiber diameters in the sub-micron range.

7.1.1. Scaffolds for tissue engineering

For engineering living tissues, biodegradable scaffold is generally considered as an indispensable element as these are used as temporary templates for cell seeding, invasion, proliferation, and differentiation prior to the regeneration of biologically functional tissue or natural extracellular matrix (ECM). There has been an increased surge in the use of electrospinning techniques to create nanofibrous scaffolds for tissue engineering as there are reports that these scaffolds positively promote cell–matrix and cell–cell interactions with the cells having a normal phenotypic shape and gene expression (Li et al., 2002; He et al., 2007). The diameter of electrospun fibers is of similar magnitude as that of fibrils in extracellular matrix (ECM) that mimics the natural tissue environment and has demonstrated effectiveness as a substrate for cell growth (Friess, 1998). Electrospinning has now become the most extensively used fabrication method for preparation of these nanofibrous scaffolds. Natural polymers are often used for preparing nanofibrous scaffolds because of their enhanced biocompatibility and bio-functional motifs such as collagen, alginate, silk protein, hyaluronic acid, fibrinogen, chitosan, starch and others and because their blending into synthetic polymers can improve the overall cytocompatibility of the scaffold (Pavlov et al., 2004; Almany and Seliktar, 2005; Wayne et al., 2005; Yoo et al., 2005; Zhang et al., 2005b). A variety of polymeric nanofibers have been considered for use as scaffolds for engineering tissues such as cartilages (Fertala et al., 2001; Li et al., 2002, 2003a; Rho et al., 2006), dermal tissue engineering (Venugopal and Ramakrishna, 2005), bones (Yoshimoto et al., 2003; Chen et al., 2006), arterial blood vessels (Huang et al., 2000; Nagapudi et al., 2002; Xu et al., 2004; Mo et al., 2004), heart (Zong et al., 2003, 2005), nerves (Silva et al., 2004; Yang et al., 2004a,b), etc. Electrospun PLGA fiber mats are considered ideal for tissue engineering scaffolds because their porosity is greater than 90%, the high surface area allows higher cellular attachment, and also because of the presence of multiple focal adhesion points on different

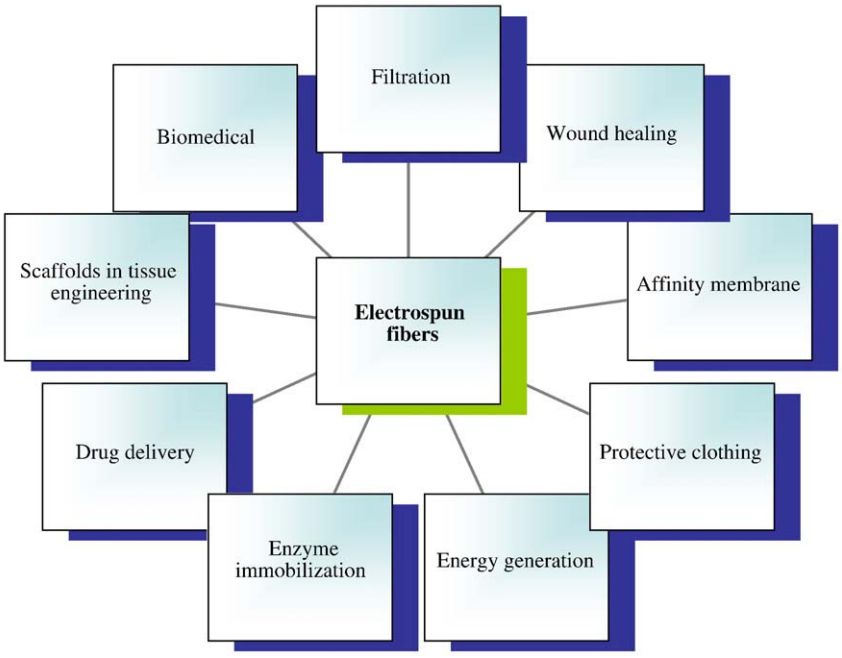

Fig. 3. Applications of electrospun fibers in different sectors.

fibers due to nano-sized fiber diameters. This electrospun fiber mat supports growth and proliferation of a wide variety of cell types for example, mouse fibroblasts adhere and spread well on PLGA nanofibers according to fiber orientation (Li et al., 2002; Geng et al., 2005). Silk fibroin fiber scaffolds containing bone morphogenetic factor 2 (BMP-2) and/or nanoparticles of hydroxypetite (nHAP) via electrospinning have been used for *in vitro* bone formation from human bone marrow-derived mesenchymal stem cells (hMSCs) and suggest that nanofibrous scaffolds of silk fibroin serve as ideal candidates for bone tissue engineering (Li et al., 2006b). There is an increase in the incorporation of marrow stromal cells (MSC) into cartilage and bone tissue engineering strategies because of their ability to differentiate into multiple cell lineages and it was also found that electrospun PCL scaffolds support the attachment, proliferation and differentiation of MSCs into adipogenic, chondrogenic, or osteogenic lineages based upon the culture media selected. The cell biocompatibility of electrospun fibrous scaffolds with MSCs has also been demonstrated by using PLGA electrospun nanofibrous scaffolds and *B. mori* silkworm silk fibroin/PEO composite electrospun scaffolds in two separate studies through the evaluation of the attachment and proliferation of MSCs in the scaffolds (Li et al., 2002, 2005a; Yoshimoto et al., 2003; Tuan et al., 2003; Jin et al., 2004). The initial excitement about the use of nanofibrous matrix for tissue engineering applications is diminishing due to the fact that, inherently, very low pore size of the mat inhibits cell infiltration inside the electrospun matrix, leading to almost two-dimensional tissues which eventually fail to simulate the physiological 3D tissue micro-environment. Various attempts are being made to improve the porosity level, and enhance cell infiltration. In order to get large pore size and high porosity Ki et al. (2007) have suggested a novel method of electrospinning silk fibroin by using different collecting parts and where the nanofibers were dropped directly on the coagulation bath containing methanol below the spinneret. Wet spinning concept has also been reported by other research group to improve the porosity and cellular migration (Kobayashi et al., 2007). Recently, novel wet electrospinning method is used by Yokoyama et al. (2009) for formation of spongiform nanofiber 3-dimensional fabric with controlled fiber density. They have used combination of both wet spinning and electrospinning system for control of nanofiber fabric. Wet spinning solvents used are pure water, 50% tertiary-butyl alcohol (t-BuOH), 99% t-BuOH and poly (glycolic acid) is used as polymer. They have found that the surface tension of the solvents used affects the fiber density significantly.

7.1.2. Dressings for wound healing

For wound healing, an ideal dressing should has certain characteristics such as haemostatic ability, efficiency as bacterial barrier, absorption ability of excess exudates (wound fluid/pus), appropriate water vapour transmission rate, adequate gaseous exchange ability, ability to conform to the contour of the wound area, functional adhesion, i.e., adherent to healthy tissue but non-adherent to wound tissue, painless to patient and ease of removal, and finally low cost (Thomas, 1990). Current efforts using polymer nanofibrous membranes as medical dressing are still in its infancy but electrospun materials meet most of the requirements outlined for wound-healing polymer devices because their microfibrous and nanofibrous structures provide the non-woven textile with desirable properties and there are also reports of cytocompatibility and cell behaviour of normal human keratinocytes and fibroblasts onto electrospun silk fibroin nanofibrous membranes (Coffee, 1998; Smith et al., 2001; Wnek et al., 2003; Kenawy et al., 2003; Huang et al., 2003; Khil et al., 2003; Katti et al., 2004; Min et al., 2004a,b). Rho et al. (2006) have investigated the wound-healing properties of mats of electrospun type I collagen fibers on wounds in mice and they found that healing of the wounds was better with the nanofiber mats than with conventional wound care, especially in the early stages of the healing process. Apart from electrospun collagen, silk and polyurethane fibers are also used in wound dressing (Jin et al., 2002; Khil et al., 2003). Jia et al. (2007) have prepared non-woven antibacterial poly (vinyl alcohol) (PVA) membrane by electrospinning of PVA aqueous solution with addition of Ag^{+}-loaded Zirconium phosphate nanoparticles for potential use in wound healing materials and antimicrobial tests proved the efficacy of nanoparticles containing nanofibers against tested strains. Recently, Spasova et al. (2008) have also prepared fibrous poly (L-lactide) (PLLA) and biocomponent PLLA/ poly (ethylene glycol) mats by electrospinning which were coated with chitosan and found that with the increase of chitosan content, the haemostatic activity of the mats increased.

7.1.3. In drug delivery

Controlled drug release at a defined rate over a definite period of time is possible with biocompatible delivery matrices of polymers and biodegradable polymers are therefore mostly used as drug delivery systems to deliver therapeutic agents because they can be easily designed for programmed dissemination in a controlled fashion (Kost and Langer, 2001; Kenawy et al., 2002). Nanofiber mats have been applied as drug carriers in the drug delivery system because of their high functional characteristics and because the drug delivery system relies on the principle that dissolution rate of a particulate drug increases with increasing surface area of both the drug and the corresponding carrier. Importantly, the large surface area associated with nanospun fabrics allows for fast and efficient solvent evaporation, which provides the incorporated drug limited time to recrystallize which favours the formation of amorphous dispersions or solid solutions (Verreck et al., 2003). Depending on the polymer carrier used, the release of pharmaceutical dosage can be designed as rapid, immediate, delayed, or modified dissolution. A number of researchers have successfully encapsulated drugs within electrospun fibers by mixing the drugs in the polymer solution to be electrospun (Kenawy et al., 2002; Zong et al., 2002b; Luu et al., 2003; Zeng et al., 2003b). A variety of solutions containing low molecular weight drugs have been electrospun, including lipophilic drugs such as ibuprofen (Jiang et al., 2004b), cefazolin (Katti et al., 2004), rifampin, paclitaxel (Zeng et al., 2003b) and Itraconazole (Verreck et al., 2003) and hydrophilic drugs such as mefoxin (Zong et al., 2002b; Kim et al., 2004) and tetracycline hydrochloride (Kenawy et al., 2002). Few, however, have encapsulated proteins in electrospun polymer fibers (Sanders et al., 2003; Chew et al., 2005). Zong et al. (2002b) have studied the effectiveness of electrospun non-woven bioabsorbable poly (lactide-co-glycolide) (PLGA) impregnated with antibiotics (mefoxin) in reducing post-surgery adhesion on an *in vivo* rat model. Zhang et al. (2006) have demonstrated encapsulation of a model protein, fluorescein isothiocyanate conjugated bovine serum albumin, along with poly(ethylene glycol) (PEG) in poly (ε-caprolactone) (PCL) fibers by using a coaxial configuration and found a relatively smooth release of the drug over a period of five days from the electrospun nanofibrous mats. Besides the normal electrospinning process, another way to develop drug-loaded polymer nanofibers for controlled drug release is to use coaxial electrospinning and research has successfully encapsulated two kinds of medically pure drugs through this process (Loscertales et al., 2002; Huang et al., 2006).

7.2. In filtration

Polymeric nanofibers have been used in air filtration applications for more than a decade. For filtration, the channels and structural elements of a filter must be matched to the scale of the particles or droplets that are to be captured in the filter. Thus, we can take advantage of the unique properties of electrospun membranes consisting of very-small-diameter fibers. It has been realized that electrospinning is rising to the challenge of providing solutions for the removal of unfriendly particles in such submicron ranges. Generally, due to the very high surface area to volume ratio and the resulting high surface cohesion, tiny particles of the order of <0.5 mm can be easily trapped in the electrospun nanofibrous structured filters and this improves the filtration efficiency. Electrospun non-woven mats

have successfully been developed into high-performance air filters. The nanofiber membrane shows an extremely effective removal (~100% rejection) of airborne particles with diameters between 1 μm and 5 μm not only by the physical entrapment mechanism but also by the electrokinetic capture in the air filter (Kattamuri et al., 2005; Ramakrishna et al., 2006). Polymer nanofibers can also be electrostatically charged to modify the ability of electrostatic attraction of particles without increase in pressure drop to further improve filtration efficiency by integrating the spinning and charging of polymer into nanofibers in one step (Tsaia et al., 2002). Filtration efficiency, which is closely associated with fiber fineness, is one of the most important concerns for filter performance. Generally, filter efficiency increases linearly with decrease of thickness of filter membrane and applied pressure increase. The enhanced filtration efficiency at the same pressure drop is possible with fibers having diameters less than 0.5 μm (Subbiah et al., 2005). Researchers have evaluated the filtration efficiency of nylon 6 nanofilters using nanofibers of 80–200 nm in diameter and pressure drop across the filter and found that 99.993% superior filtration efficiency of nylon 6 nanofilters than commercialized high efficiency particulate air (HEPA) filter at the face velocity of 5 cm/s using 0.3 μm test particles (Ahn et al., 2006). Few research groups have successfully synthesized electrospun polyurethane cationomers (PUCs) containing different amounts of quaternary ammonium groups into non-woven nanofiber mats for use in antimicrobial nanofilter applications and showed very strong antimicrobial activities against *Staphylococcus aureus* and *Escherichia coli* (Burger et al., 2006; Jeong et al., 2007). There are also numerous examples of applying adsorptive membranes/felts for the purification of large biomolecules (e.g., plasmid DNA (Endres et al., 2003; Teeters et al., 2003), supercoiled DNA (Haber et al., 2004), and proteins (Yang et al., 1999, 2002; Zhang et al., 2008b).

7.3. As biosensors

Biosensors, which typically consist of bio-functional membrane and transducer, have been widely used for environmental, food, and clinical purposes. There are lots of parameters that affect the performance of a sensor which includes sensitivity, selectivity, response time, reproducibility, and aging, all of which are dependent directly on the property of the sensing membrane used. Because there is a strong need for detection of gases and biological substances at low concentration, sensitivity particularly, plays a very critical role. Modern biomedical sensors with advanced micro fabrication and signal-processing techniques are becoming more and more accurate and inexpensive nowadays (Figeys and Pinto, 2000). The main focus is now on miniaturization of bulky instrumentation and development of portable sensors in order to avoid the burden of accuracy and reliability and also in the development of various specific target molecules for different analytes that have exhausted all possibilities. Electrospun nanofibrous membranes have received great attention for their sensor applications because of their unique large surface area which is the most desirable property for improving the sensitivity of conductometric sensors, as larger surface area will absorb more of a gas analyte and change the sensor's conductivity more significantly. Silk fibroin membranes-based biosensors have been extensively used for analysing various substances such as glucose, hydrogen peroxide and uric acid (Liu et al., 1996; Zhang, 1998; Zhang et al., 1998). Apart from this, the literature shows the involvement of other electrospun polymers such as polyaniline, polypyrrole, polyamic acid, nylon-6, poly(vinyl alcohol)(PVA)and poly (acrylic acid)-poly (pyrene methanol), also as sensing interfaces (Wang et al., 2002, 2004; Jianrong et al., 2004; Ramanathan et al., 2005; Lala et al., 2007). Recently, efforts have been made to produce nanofibers for electrochemical sensors as well. Therefore, nanofibers that have a very large surface area would be ideal for electrochemical biosensors as well. Optical sensors are relatively new and not much work has been carried out in this field. Recent progress in biomedical technology has mainly focussed on the development of novel sensor products with new applications.

7.4. Protective clothing applications

Ideally, protective clothing should have some essential properties such as, light weight, breathable fabric, air and water vapour permeability, insolubility in all solvents and enhanced toxic chemical resistance. Electrospun nanofiber membranes have been recognized as potential candidates for protective clothing applications, because of their light weight, large surface area, high porosity (breathable nature), great filtration efficiency, resistant to penetration of harmful chemical agents in aerosol form and their ability to neutralize the chemical agents without impedance of the air and water vapour permeability to the clothing (Gibson et al., 1999; Schreuder-Gibson et al., 2002). A variety of methods for modification of nanofiber surfaces have been tried in order to get improved protection against toxins. One protection method that has been used includes chemical surface modification and attachment of reactive groups such as oximes, cyclodextrins, and chloramines that bind and detoxify warfare agents (McCreery, 1997; Ramakrishna et al., 2006).

7.5. Energy generation applications

Polymeric conductive membranes also have potential for applications such as, electrostatic dissipation, corrosion protection, electromagnetic interference shielding, photovoltaic device, fabrication of tiny electronic devices or machines such as Schottky junctions, sensors and actuators etc., as the rate of electrochemical reactions is proportional to the surface area of the electrode (Senecal et al., 2002; Norris et al., 2000). Conductive nanofibrous membranes are also quite suitable for use as porous electrodes in developing high performance batteries and polymer electrolyte membrane fuel cells (PEMFCs) due to its high porosity and inherent large total surface area. Polymer batteries have been developed for cellular phones to replace conventional, bulky lithium batteries. The components of polymer batteries are a carbon anode, a lithium cobalt oxide cathode, and a polymer gel electrolyte. Conductive nanofibers offers noteworthy properties of polymer batteries, for example, less electrolyte leakage, high dimension flexibility, and high energy density per weight (Choi et al., 2003) However, there is still a need to improve energy density per weight of polymer batteries to increase their market share.

7.6. In immobilization of enzymes

Immobilization of enzymes on inert, insoluble materials is an active area of research for improving the functionality and performance of enzymes for bioprocessing applications as immobilized enzymes offer several advantages such as reusability, better control reaction and are more stable than soluble ones (Jia et al., 2002; Bacheva et al., 2003; Xie and Hsieh, 2003; Onal and Telefoncu, 2003; Yang et al., 2004d). The performance of immobilized enzymes depends greatly on the characters and structure of the carrier materials and on modification of the carriers, such as rendering biocompatibility, hydrophilicity, etc (Ye et al., 2005). Nevertheless, even for the modified supports, the enzyme loading is usually considerably low. Alternatively, porous material such as membranes, gel matrices, and porous particles have been used to achieve high enzyme loading (Martinek et al., 1977; Cantarella et al., 1988; Bhardwaj et al., 1996; Baran et al., 1997; Arica et al., 1999; Wang et al., 2001; Huang et al., 2001c; Jia et al., 2002,). The fine porous structure of electrospun fibrous membranes can effectively relieve the diffusion resistance of the substrates/products and can greatly increase the catalyzing ability of the immobilized enzymes due to the large specific surface area. Nanofibrous membranes offer advantages such as; these can be processed into various structures such as

non-woven mats, or well-aligned arrays and are more conveniently recovered and more durable than other nanoparticles or carbon nanotubes (Wang et al., 2006). For the first time, Jia et al. (2002) have prepared electrospun polystyrene nanofibers for immobilization of α-chymotrypsin and found 65% hydrolytic activity of immobilized enzyme than that of the free enzyme. Pristine silk fibroin (SF) nanofibers have also been used for α chymotrypsin immobilization 90% activity retainment has been observed for SF fibers of 205 nm diameter even after 24 h (Lee et al., 2005b). For lipase immobilization, Ye et al. (2006) have fabricated nanofibers electrospun from poly (acrylonitrile-*co*-maleic acid) and the amount and activity retention of lipase immobilized on the nanofibers were 21.2 mg/g fibers and 37.6%, respectively, while those on the corresponding hollow fiber membrane were only 2.36 mg/g membrane and 33.9%. Li et al. (2007) used an amidination reaction, using pristine polyacrylonitrile nanofibers as supports for immobilization of lipase and showed that conjugation method gave higher enzyme loading than other immobilization methods. Recently, an intriguing approach has been the use of nanostructure materials which provide a large surface area for the attachment of enzymes and biodegradable materials such as nanofibers of poly (ε-caprolactone) and poly (D, L-lactic-*co*-glycolic acid)-*b*-poly (ethylene glycol)-NH2 (PLGA-*b*-PEG-NH2) block copolymer which have been used as supports to covalently immobilize lysozyme (Kim et al., 2005c; Kim and Park, 2006). The co-electrospinning method, a simple route to immobilize enzymes into nanofibers with substantially high enzyme loading capability (up to 50% of the fibers) has been used by researchers. They have also discussed two different methods, surface attachment and encapsulation for enzyme immobilization using nanofibers as hosts (Wang and Hsieh, 2008). However, the low catalytic efficiency and stability of enzymes, difficulty in fabricating in batches and availability of very few tools for evaluation have been considered as barriers for the development of large-scale operations and applications (Ding et al., 2004; Kidoaki et al., 2005; Theron et al., 2005).

7.7. As affinity membrane

Affinity membranes are a broad class of membranes that selectively capture specific target molecules (or ligates) by immobilizing a specific or ligand onto the membrane surface and reflect technological advances in both fixed-bed liquid chromatography and membrane filtration, and combine both the outstanding selectivity of the chromatography resins and the reduced pressure drops associated with filtration membranes (Tomas and Kula, 1995; Klein, 2000). Few works have been reported on the application of the electrospun nanofiber mesh as affinity membrane and for this the surface must be functionalized prior with ligands. In most cases, the ligand molecules should be covalently attached on the membrane to prevent leaching of the ligands (Bamford et al., 1992; Gibson et al., 2001; Ma et al., 2005b; Gopal et al., 2006). Surface modified electrospun polyurethane nanofiber membrane has been used with Protein A for IgG purification (Bamford et al., 1992). For protein purification, the affinity membrane should be made up of hydrophilic materials which usually have lower non-specific protein adsorption than hydrophobic synthetic polymers, for example, cellulose is a hydrophilic material widely used in membrane preparation. Affinity membranes also provide an alternative approach for removing organic molecules from waste water. For example, β-cyclodextrin, a cyclic oligosaccharide with a hydrophobic interior and hydrophilic exterior has been introduced into a poly (methyl methacrylate) nanofiber membrane using a physical mixing method for organic waste removal that can capture hydrophobic organic molecules from water by forming an inclusion complex is used for affinity membrane application (Kaur et al., 2006). Recently Ma and Ramakrishna (2008) have prepared and characterized Protein A/G functionalized electrospun regenerated cellulose nanofiber mesh as affinity membrane for immunoglobulin G purification.

7.8. In cosmetics

Electrospun polymer nanofibers have been also utilized with or without various additives as a cosmetic skin care mask for the treatment of skin healing, skin cleansing, or other therapeutical and medical properties (Smith et al., 2001). The electrospun nanofibrous skin mask has advantage of high surface area which facilitates better utilization and also speeds up the transfer rate of the additives to the skin. The electrospun nanofibrous cosmetic skin mask can be introduced gently and painlessly and also directly to the three-dimensional topography of the skin to provide healing or care treatment to the skin (Huang et al., 2003). For skin health and renewal, skin-revitalizing factors can be impregnated into nanofiber masks (Ramakrishna et al., 2006). Due to very small pore size and high surface area to volume ratio, electrospun nanofibers have the potential to be used as skin masks.

8. Future prospects

For improvement in the applicability of these fibers, various new innovations electrospinning are being used. These innovations include coaxial electrospinning, mixing and multiple electrospinning, core shelled electrospinning, blow assisted electrospinning and others. Coaxial electrospinning includes fabrication of nanofibers from two polymers which utilizes coaxial capillary spinneret and as a result a core of one polymer and shell of the other are formed (Sun et al., 2003). With this technology, some polymers which are difficult to process are co-electrospun and form a core inside the shell of other polymer. This method gains attention as it provides novel properties and functionalities of nanoscale devices through the combination of polymeric materials in the axial and radial direction. The electrospun nanofibers are also used as drug delivery vehicles, but due to large surface area and high porosity, a significant burst release is observed. Coaxial method is commonly used for controlling the burst release of drugs, as the shell of the polymer acts as diffusion barrier for drugs. Other new innovations will also offer various advantages. Blowing-assisted electrospinning helps in spinning of high molecular weight polymers which was otherwise difficult to spin by solution electrospinning. Recently, there has been wide interest in using the nanofibrous membranes as tissue engineering scaffolds. A nanoscale fibrous scaffold more closely mimics the extracellular matrix than macroscale scaffolds and provides a three dimensional (3D) environment. With nanofibrous scaffolds, cell adhesion, proliferation and differentiation of several types of cells have been observed including bone marrow stem cells too. As a tissue engineering scaffolds, nanofibers of various polymers can be used for osteogenesis, wound healing, skin regeneration. Therefore, an electrospun nanofibrous scaffold holds great potential to be used for tissue engineering applications in future. A recent research has demonstrated the use of nanofibers in making nanowires as the incorporation of carbon nanotubes within the fibrous structure provides anisotropic properties such as electrical and thermal conductivity (Hunley and Long, 2008). With the advent of copolymerization and polymer mixtures, attainment of the desired physical and biological properties of nanofibrous mesh has become possible now. There is ongoing research for the improvement of nanofiber properties and the scale up of this process. In future electrospun nanofibers will prove to be a promising candidate for a wider range of applications.

9. Conclusion

(1) Electrospinning is a simple, versatile, and cost-effective technology which generates non-woven fibers with high surface area to volume ratio, porosity and tunable porosity. Because of these properties this process seems to be a promising candidate for various applications especially tissue engineering applications.
(2) Solution and processing parameters such as viscosity, molecular weight, concentration of the polymer, applied voltage, tip

to collector distance, conductivity, etc. significantly affect the fiber morphology and by manipulation of these parameters one can get desired properties for specific application.

(3) Melt electrospinning, an alternative means of electrospinning, apart from solution, is also available that is done with polymer melts, which alleviates the requirement of solvents.

(4) Nanofibers have been characterized by several techniques such as scanning electron microscopy, transmission electron microscopy, atomic force microscopy, nuclear magnetic resonance, etc. physical, chemical and mechanical characterizations of nanofibers have been done.

(5) Spun fibers are increasingly being used in a variety of applications such as, tissue engineering scaffolds, wound healing, drug delivery, immobilization of enzymes, as membrane in biosensors, protective clothing, cosmetics, affinity membranes, filtration applications etc.

(6) Despite of several advantages and success of electrospinning there are some critical limitations in this process such as small pore size and lack of proper cellular infiltration inside the fibers. Several attempts in these directions are being made to improve the design and cellular migration through multilayering, inclusion of heprasil and blending with polymers with different degradation behaviour. In general, the electrospinning process shows excellent promise for tissue engineering and regenerative medicine.

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References

Adomaviciute E, Milasius Rimvydas. The influence of applied voltage on poly (vinyl alcohol) (PVA) nanofibre diameter. Fibers Text East Eur 2007;15:64–5.

Ahn YC, Park SK, Kim GT, Hwang YJ, Lee CG, Shin HS, et al. Development of high efficiency nanofilters made of nanofibers. Curr Appl Phys 2006;6:1030–5.

Alessandrino A, Marelli B, Arosio C, Fare S, Tanzi MC, Freddi G. Electrospun silk fibroin mats for tissue engineering. Eng Life Sci 2008;8(3):219–25.

Almany L, Seliktar D. Biosynthetic hydrogel scaffolds made from fibrinogen and polyethylene glycol for 3d cell cultures. Biomaterials 2005;26:2467–77.

Altman GH, Diaz F, Jakuba C, Calabro T, Horan RL, Chen J, et al. Silk-based biomaterials. Biomaterials 2003;24:401–16.

Arica MY, Baran T, Denizli A. β-galactosidase immobilization into poly (hydroxyethyl methacrylate) membrane and performance in a continuous system. J Appl Polym Sci 1999;72:1367–73.

Ayutsede J, Gandhi M, Sukigara S, Micklus M, Chen HE, Ko F. Regeneration of *Bombyx mori* silk by electrospinning. Part 3: characterization of electrospun nonwoven mat. Polymer 2005;46:1625–34.

Bacheva AV, Baibak OV, Belyaeva AV, Oksenoit ES, Velichko TI, Lysogorskaya EN, et al. Activity and stability of native and modified subtilisins in various media. Biochemistry 2003;68:1261–6.

Balakrishnan B, Jayakrishnan A. Self-cross-linking biopolymers as injectable in situ forming biodegradable scaffolds. Biomaterials 2005;26:3941–51.

Bamford CH, Al-Lamee KG, Wear PTJ. Studies of a novel membrane for affinity separations. I. Functionalisation and protein coupling. J Chromatogr 1992;606: 19–31.

Baran T, Arica Y, Denizli A, Hasirci V. Comparison of β-galactosidase immobilization by entrapment in and adsorption on poly (2-hydroxyethyl methacrylate) membranes. Polym Int 1997;44:530–6.

Barnes CP, Sell SA, Knapp DC, Walpoth BH, Brand DD, Bowlin GL. Preliminary investigation of electrospun collagen and polydioxanone for vascular tissue engineering applications. Int J Electrospun Nanofibers Appl 2007;1:73–87.

Baumgarten PK. Electrostatic spinning of acrylic microfibers. J Colloid Interface Sci 1971;36:71–9.

Berry JP. Electrostatically Produced Structures and Methods of Manufacturing. US Patent 4965110, 1990.

Bhardwaj A, Lee J, Glauner K, Ganapathi S, Bhattacharyya D, Butterfield DA. Biofunctional membranes: an EPR study of active site structure and stability of papain noncovalently immobilized on the surface of modified poly- (ether) sulfone membranes through the avidin–biotin linkage. J Membr Sci 1996;119:241–52.

Bhattarai N, Cha DI, Bhattarai SR, Khil MS, Kim HY. Biodegradable electrospun mat: novel block copolymer of poly (p-dioxanone-co-Llactide)-block-poly (ethylene glycol). J Polym Sci B Polym Phys 2003;41:1955–64.

Bhattarai SR, Bhattarai N, Yi HK, Hwang PH, Cha DI, Kim HY. Novel biodegradable electrospun membrane: scaffold for tissue engineering. Biomaterials 2004;25: 2595–602.

Bognitzki M, Frese T, Wendorff JH, Greiner A. Submicrometer shaped polylactide fibers by electrospinning. Polym Mater Sci Eng 2000;82:115–6.

Boland ED, Wnek GE, Simpson DG, Pawlowski KJ, Bowlin GL. Tailoring tissue engineering scaffolds using electrostatic processing techniques: a study of poly (glycolic acid) electrospinning. J Macromol Sci Pure Appl Chem A 2001;38:1231–43.

Boland ED, Telemeco TA, Simpson DG, Wnek GE, Bowlin GL. Utilizing acid pretreatment and electrospinning to improve biocompatibility of poly (glycolic acid) for tissue engineering. J Biomed Mater Res B Appl Biomater 2004a;71B:144–52.

Boland ED, Wnek GE, Bowlin GL. Poly (Glycolic Acid). In: Bowlin GL, Wnek GE, editors. Encyclopedia of biomaterials and biomedical engineering, vol. 2. NewYork: Marcel Dekker, Inc; 2004b. p. 1246–53.

Boland ED, Matthews JA, Pawlowski KJ, Simpson DG, Wnek GE, Bowlin GL. Electrospinning collagen and elastin : preliminary vascular tissue engineering. Front Biosci 2004c;9: 1422–32.

Bornat, A., Production of Electrostatically Spun Products, US Patent 4689186, 1987.

Buchko CJ, Chen LC, Shen Y, Martin DC. Processing and microstructural characterization of porous biocompatible protein polymer thin films. Polymer 1999;40: 7397–407.

Bulpitt P, Aeschlimann D. New strategy for chemical modification of hylauronic acid: preparation of functionalized derivatives and their use in the formation of novel biocompatible hydrogels. J Biomed Mater Res 1999;47:152–69.

Burger C, Hsiao BS, Chu B. Nanofibrous marterials and their applications. Annu Rev Mater Res 2006;36:333–68.

Cai SS, Liu YC, Shu XZ, Prestwich GD. Injectable glycosaminoglycan hydrogels for controlled release of human basic fibroblast growth factor. Biomaterials 2005;26: 6054–67.

Campoccia D, Doherty P, Radice M, Brun P, Abatagelo G, Williams DF. Semi-synthetic resorbable materials from hyaluronan esterification. Biomaterials 1998;19:2101–27.

Cantarella M, Cantarella L, Alfani F. Entrapping of acid phosphatatse in poly (2-hydroxyethyl methacrylate) matrices: preparation and kinetic properties. Br Polym J 1988;20:477–85.

Cappello J, MacGrath KP, Viney C. Spinning of protein polymers fibers. In: Kaplan D, Adams WW, Farmer B, editors. Silk polymers. Washington, DC: ACS; 1994. p. 311–27.

Casper CL, Stephens JS, Tassi NG, Chase DB, Rabolt JF. Controlling surface morphology of electrospun polystyrene fibers: effect of humidity andmolecular weight in the electrospinning process. Macromolecules 2004;37:573–8.

Chen VJ, Ma PX. Nano-fibrous poly (L -lactic acid) scaffolds with interconnected spherical macropores. Biomaterials 2004;25:2065–73.

Chen ZH, Foster MD, Zhou WS, Fong H, Reneker DH, Resendes R, et al. Structure of poly (ferrocenyldimethylsilane) in electrospun nanofibers. Macromolecules 2001;34: 6156–8.

Chen JL, Chu B, Hsiao BS. Mineralization of hydroxyapatite in electrospun nanofibrous poly (L-lactic acid) scaffolds. J Biomed Mater Res 2006;79A:307–17.

Chen Z, Mo X, Qing F. Electrospinning of collagen–chitosan complex. Mater Lett 2007;61:3490–4.

Chen M, Michaud H, Bhowmick S. Controlled vacuum seeding as a means of generating uniform cellular distribution in electrospun polycaprolactone (PCL) scaffolds. J Biomech Eng 2009;131:074521.

Chew SY, Wen J, Yim EK, Leong KW. Sustained release of proteins from electrospun biodegradable fibers. Biomacromolecules 2005;6:2017–24.

Chew SY, Wen Y, Dzenis Y, Leong KW. The role of electrospinning in the emerging field of nanomedicine. Curr Pharm Des 2006a;12:4751–70.

Chew SY, Hufnagel TC, Lim CT, Leong KW. Mechanical properties of single electrospun drug-encapsulated nanofibres. Nanotechnology 2006b;17:3880–91.

Choi SW, Jo SM, Lee WS, Kim YR. An electrospun poly (vinylidene fluoride) nanofibrous membrane and its battery applications. Adv Mater 2003;15:2027–32.

Chong EJ, Phan TT, Lim IJ, Zhang YZ, Bay BH, Ramakrishna S, et al. Evaluation of electrospun PCL/gelatin nanofibrous scaffold for wound healing and layered dermal reconstitution. Acta Mater 2007;3:321–30.

Chun I, Reneker DH, Fong H, Fang X, Deitzel J, Tan NB, et al. Carbon nanofibers from polyacrylonitrile and mesophase pitch. J Adv Mater 1999;31:36–41.

Clark RA, Lanigan JM, DellaPelle P, Manseau E, Dvorak HF, Colvin RB. Fibronectin and fibrin provide a provisional matrix for epidermal cell migration during wound reepithelialization. J Invest Dermatol 1982;79:264–9.

Coffee RA. A dispensing device and method for forming material. PCT International Application No: PCT/GB97/01968; 1998.

Cooley JF. Apparatus for electrically dispersing fluids. US Patent Specification 692631, 1902.

Cort JR, Andersen NH. Formation of a molten-globule-like state of myoglobin in aqueous hexafluoroisopropanol. Biochem Biophys Res Commun 1997;233:687–91.

Cuenot S, Demoustier-Champagne S, Nysten B. Elastic modulus of polypyrrole nanotubes. Phys Rev Lett 2000;85:1690–3.

Cuenot S, Fretigny C, Demoustier-Champagne S, Nysten B. Measurement of elastic modulus of nanotubes by resonant contact atomic force microscopy. J Appl Phys 2003;93:5650–5.

Cui W, Zhou S, Li X, Weng J. Drug-loaded biodegradable polymeric nanofibers prepared by electrospinning. Tissue Eng 2006;12:1070.

Dal Pra I, Freddi G, Minic J, Chiarini A, Armato U. De novo engineering of reticular connective tissue in vivo by silk fibroin nonwoven materials. Biomaterials 2005;26: 1987–99.
Dalton PD, Calvet JL, Mourran A, Klee D, Möller M. Melt electrospinning of poly-(ethylene glycol-block-ε-caprolactone). Biotechnol J 2006a;1:998-1006.
Dalton PD, Klinkhammer K, Salber J, Klee D, Moller M. Direct in vitro electrospinning with polymer melts. Biomacromolecules 2006b;7:686–90.
Deitzel JM, Kleinmeyer J, Harris D, Tan NCB. The effect of processing variables on the morphology of electrospun nanofibers and textiles. Polymer 2001;42:261–72.
Deitzel JM, Kosik W, McKnight SH, Ten NCB, Desimone JM, Crette S. Electrospinning of polymer nanofibers with specific surface chemistry. Polymer 2002;43:1025–9.
Demir MM, Yilgor I, Yilgor E, Erman B. Electrospinning of polyurethane fibers. Polymer 2002;43:3303–9.
DiNardo, N.J., Nanoscale Characterization of Surfaces and Interfaces. VCH: Federal Republic of Germany, 1994, 163 S.
Ding B, Kim HY, Lee SC, Shao CL, Lee DR, Park SJ, et al. Preparation and characterization of a nanoscale poly (vinyl alcohol) fiber aggregate produced by an electrospinning method. J Polym Sci B Polym Phys 2002;40:1261–8.
Ding B, Kimura E, Sato T, Fujita S, Shiratori S. Fabrication of blend biodegradable nanofibrous nonwoven mats via multi-jet electrospinning. Polymer 2004;45:1895–902.
Doshi J, Reneker DH. Electrospinning process and applications of electrospun fibers. J Electrost 1995;35:151–6.
Dosunmu OO, Chase GG, Kantaphinan W, Reneker DH. Electrospinning of polymer nanofibres from multiple jets on a porous tubular surface. Nanotechnology 2006;17: 1123–7.
Drozin VG. The electrical dispersion of liquids as aerosols. J Colloid Sci 1955;10:158–64.
Duan B, Dong C, Yuan X, Yao K. Electrospinning of chitosan solutions in acetic acid with poly(ethylene oxide). J Biomater Sci Polym Ed 2004;15:797–811.
Eichhorn SJ, Sampson WW. Statistical geometry of pores and statistics of porous nanofibrous assemblies. J R Soc Interface 2005;2:309–18.
Ekaputra AK, Prestwich GD, Cool SM, Hutmacher DW. Combining electrospun scaffolds with electrosprayed hydrogels leads to three-dimensional cellularization of hybrid constructs. Biomacromolecules 2008;9:2097–103.
Ekaputra AK, Zhou Y, Cool SM, Hutmacher DW. Composite Electrospun Scaffolds for Engineering Tubular Bone Grafts. Tissue Eng A 2009;15:3779–88.
Endres HN, Johnson JAC, Ross CA, Welp JK, Etzel M. Evaluation of an ion-exchange membrane for the purification of plasmid DNA. Biotechnol Appl Biochem 2003;37:259–66.
Fang X, Reneker DH. DNA fibers by electrospinning. J Macromol Sci Phys B 1997;36: 169–73.
Fertala A, Han WB, Ko FK. Mapping critical sites in collagen II for rational design of gene-engineered proteins for cell-supporting materials. J Biomed Mater Res 2001;57: 48–58.
Figeys D, Pinto D. Lab-on-a-chip: a revolution in biological and medical sciences—a look at some of the basic concepts and novel components used to construct prototype devices. Anal Chem 2000;72:330A–5A.
Fong H, Reneker DH. Elastomeric nanofibers of styrene–butadiene–styrene tri-block copolymers. J Polym Sci B Polym Phys 1999;37:3488–93.
Fong H, Chun I, Reneker DH. Beaded nanofibers formed during electrospinning. Polymer 1999;40:4585–92.
Fong H, Liu WD, Wang CS, Vaia RA. Generation of electrospun fibers of nylon 6 and nylon 6-montmorillonite nanocomposite. Polymer 2002;43:775–80.
Formhals, A., Process and apparatus for preparing artificial threads. U.S. Patent No. 1, 975, 504, 1934.
Fridrikh SV, Yu JH, Brenner MP, Rutledge GC. Controlling the fiber diameter during electrospinning. Phys Rev Lett 2003;90:144502–4.
Friess W. Collagen—biomaterial for drug delivery. Eur J Pharm Biopharm 1998;45: 113–36.
Geng X, Kwon OH, Jang J. Electrospinning of chitosan dissolved in concentrated acetic acid solution. Biomaterials 2005;26:5427–32.
Gibson PW, Schreuder-Gibson HL, Rivin D. Electrospun fiber mats: transport properties. AIChE J 1999;45:190–5.
Gibson PW, Schreuder-Gibson HL, Rivin D. Transport properties of porous membranes based on electrospun nanofibers. Colloids Surf, A Physicochem Eng Asp 2001;187: 469–81.
Giza E, Ito H, Kikutani T, Okui N. Fiber structure formation in high-speed melt spinning of polyamide 6/clay hybrid nanocomposite. J Macromol Sci B 2000;39:545–59.
Gopal R, Kaur S, Ma ZW, Chan C, Ramakrishna S, Matsuura T. Electrospun nanofibrous filtration membrane. J Membr Sci 2006;281:581–6.
Gosline JM, Demont ME, Denny MW. The structure and properties of spider silk. Endeavour 1986;10:37–43.
Grant S, Blair HS, Mckay G. Structural studies on chitosan and other chitin derivatives. Macromol Chem 1989;190:2279–86.
Gui-Bo Y, You-Zhu Z, Shu-Dong W, De-Bing S, Zhi-Hui D, Wei-Guo F. Study of the electrospun PLA/silk fibroin–gelatin composite nanofibrous scaffold for tissue engineering. J Biomed Mater Res Part A 2010;93:158–63.
Gupta P, Elkins C, Long TE, Wilkes GL. Electrospinning of linear homopolymers of poly (methylmethacrylate): exploring relationships between fiber formation, viscosity, molecular weight and concentration in a good solvent. Polymer 2005;46:4799–810.
Haber C, Skupsky J, Lee A, Lander R. Membrane chromatography of DNA: conformation-induced capacity and selectivity. Biotechnol Bioeng 2004;88:26–34.
Haghi AK, Akbari M. Trends in electrospinning of natural nanofibers. Phys Status Solidi 2007;204:1830–4.
Hakkarainen M. Aliphatic polyesters: abiotic and biotic degradation and degradation products. Adv Polym Sci 2002;157:113–38.
Hao X, Zhang Xuequan. Syndiotactic 1, 2-polybutadiene fibers produced by electro-spinning. Mater Lett 2007;61:1319–22.
Haque MA, Saif MTA. A review of MEMS-based microscale and nanoscale tensile and bending testing. Exp Mech 2003;43:248–55.
Hasegawa M, Isogai A, Onabe F, Usuda M. Dissolving states of cellulose and chitosan in trifluoroacetic acid. J Appl Polym Sci 1992;45:1857–63.
Hayati I, Bailey AI, Tadros TF. Investigations into the mechanisms of electrohydrody-namic spraying of liquids. 1. Effect of electric-field and the environment on pendant drops and factors affecting the formation of stable jets and atomization. J Colloid Interface Sci 1987;117:205–21.
He J, Wan YQ, Yu JY. Scaling law in electrospinning: relationship between electric current and solution flow rate. Polymer 2005;46:2799–801.
He W, Horn SW, Hussain MD. Improved bioavailability of orally administered mifepristone from PLGA nanoparticles. Int J Pharm 2007;334:173–8.
Ho BC, Lee YD, Chin WK. Thermal degradation of polymethacrylic acid. J. Polym. Sci.: Polym Chem 1992;30:2389–97.
Hohman MM, Shin M, Rutledge G, Brenner MP. Electrospinning and electrically forced jets. II. Applications. Phys Fluids 2001;13:2221–36.
Hokputsa S, Jumel K, Alexander C, Harding SE. Hydrodynamic characterization of chemically degraded hyaluronic acid. Carbohydr Polym 2003;52:111–7.
Hong DP, Hoshino M, Kuboi R, Goto Y. Clustering of fluorine-substituted alcohols as a factor responsible for their marked effects on proteins and peptides. J Am Chem Soc 1999;121:8427–33.
Horan RL, Antle K, Collette AL, Wang Y, Huang J, Moreau JE, et al. In vitro degradation of silk fibroin. Biomaterials 2005;26:3385–93.
How TV. Synthetic Vascular Grafts and Methods of Manufacturing Such Grafts. US Patent 4552707, 1985.
How TV, Guidoin R, Young SK. Engineering design of vascular prostheses, proceedings of the institution of mechanical engineers. Part H. J Eng Med 1992;206:61–72.
Hsu CM, Shivkumar SN. N-dimethylformamide additions to the solution for the electrospinning of poly (e-caprolactone) nanofibers. Macromol Mater Eng 2004a;289: 334–40.
Hsu CM, Shivkumar S. Nano-sized beads and porous fiber constructs of poly (vepsiln-caprolactone) produced by electrospinning. J Mater Sci 2004b;39:3003–13.
Huang CF, Chang FC. Comparison of hydrogen bonding interaction between PMMA/PMAA blends and PMMA-co-PMAA copolymers. Polymer 2003;44:2965–74.
Huang L, McMillan RA, Apkarian RP, Pourdeyhimi B, Conticello VP, Chaikof EL. Generation of synthetic elastin-mimetic small diameter fibers and fiber networks. Macromolecules 2000;33:2989–97.
Huang L, Nagapudi K, Apkarian RP, Chaikof EL. Engineered collagen-PEO nanofibers and fabrics. J Biomater Sci Polym Ed 2001a;12:979–93.
Huang L, Apkarian RP, Chaikof EL. High-resolution analysis of engineered type I collagen nanofibers by electron microscopy. Scanning 2001b;23:372–5.
Huang FC, Ke CH, Kao CY, Lee WC. Preparation and application of partially porous poly (styrene-divinylbenzene) particles for lipase immobilization. J Appl Polym Sci 2001c;80:39–46.
Huang ZM, Zhang YZ, Kotaki M, Ramakrishna S. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. Compos Sci Technol 2003;63:2223–53.
Huang ZM, Zhang YZ, Ramakrishna S, Lim CT. Electrospinning and mechanical characterization of gelatin nanofibers. Polymer 2004;45:5361–8.
Huang ZM, He CL, Yang A, Zhang YZ, Han XJ, Yin J, et al. Encapsulating drugs in biodegradable ultrafine fibers through co-axial electrospinning. J Biomed Mater Res A 2006;77:169–79.
Hubbell JA. Biomaterials in tissue engineering. Biotechnology 1995;13:565–76.
Hunley MT, Long TE. Electrospinning functional nanoscale fibers: a perspective for the future. Polym Int 2008;57:385–9.
Ikada Y, Tabata Y. Protein release from gelatin matrices. Adv Drug Deliv Rev 1998;31: 287–301.
Inai R, Kotaki M, Ramakrishna S. Structure and properties of electrospun PLLA single nanofibres. Nanotechnology 2005;16:208–13.
Jalili R, Hosseini SA, Morshed M. The effects of operating parameters on the morphology of electrospun polyacrilonitrile nanofibres. Iran Polym J 2005;14:1074–81.
Jalili R, Morshed M, Abdolkarim S, Ravandi H. Fundamental parameters affecting electrospinning of PAN nanofibers as uniaxially aligned fibers. J Appl Polym Sci 2006;101:4350–7.
Jarusuwannapoom T, Hongroijanawiwat W, Jitjaicham S, Wannatong L, Nithitanakul M, Pattamaprom C, et al. Effect of solvents on electro-spinnability of polystyrene solutions and morphological appearance of resulting electrospun polystyrene fibers. Eur Polym J 2005;41:409–21.
Jeong EH, Yang J, Youk JH. Preparation of polyurethane cationomer nanofiber mats for use in antimicrobial nanofilter applications. Mater Lett 2007;61:3991–4.
Jia HF, Zhu GY, Vugrinovich B, Kataphinan W, Reneker DH, Wang P. Enzyme-carrying polymeric nanofibers prepared via electrospinning for use as unique biocatalysts. Biotechnol Prog 2002;18:1027–32.
Jia J, Duan YY, Wang SH, Zhang SF, Wang ZY. Preparation and characterization of antibacterial silver-containing nanofibers for wound dressing applications. J US-China Med Sci 2007;4:52–4.
Jiang HL, Fang DF, Hsiao BS, Chu B, Chen WL. Optimization and characterization of dextran membranes prepared by electrospinning. Biomacromolecules 2004a;5: 326–33.
Jiang HL, Fang DF, Hsiao D, Chu B, Chen WL. Preparation and characterization of ibuprofen- loaded poly (lactide-co-clycolide)/poly (ethyleneglycol)-g-chitosan electrospun membranes. J Biomater Sci Polym Ed 2004b;15:279–96.
Jianrong C, Yuqing M, Nongyue H, Xiaohua W, Sijiao L. Nanotechnology and biosensors. Biotechnol Adv 2004;22:505–18.
Jin HJ, Fridrikh SV, Rutledge GC, Kaplan DL. Electrospinning *Bombyx mori* silk with poly (ethylene oxide). Biomacromolecules 2002;3:1233–9.

Jin HJ, Chen J, Karageorgiou V, Altman GH, Kaplan DL. Human bone marrow stromal cell responses to electrospun silk fibroin mats. Biomaterials 2004;25:1039–47.
Jing Z, Xu XY, Chen XS, Liang QZ, Bian XC, Yang LX, et al. Biodegradable electrospun fibers for drug delivery. J Control Release 2003;92:227–31.
Jun Z, Hou H, Schaper A, Wendorff JH, Greiner A. Poly-L-lactide nanofibers by electrospinning — influence of solution viscosity and electrical conductivity on fiber diameter and fiber morphology. e-Polym 2003;9:1–9.
Kattamuri N, Shin JH, Kang B, Lee CG, Lee JK, Sung C. Development and surface characterization of positively charged filters. J Mater Sci 2005;40:4531–9.
Katti DS, Robinson KW, Ko FK, Laurencin CT. Bioresorbable nanofiber-based systems for wound healing and drug delivery: optimization of fabrication parameters. J Biomed Mater Res 2004;70B:286–96.
Kaur S, Gopal R, Kotaki M, Ma ZW, Ramakrishna S. Oligosaccharide functionalized nanofibrous membrane. Int J Nanosci 2006;5:1-11.
Kawai K, Suzuki S, Tabata Y, Ikada Y, Nishimura Y. Accelerated tissue regeneration through incorporation of basic fibroblast growth factor-impregnated gelatin microspheres into artificial dermis. Biomaterials 2000;21:489–99.
Kenawy ER, Bowlin GL, Mansfield K, Layman J, Simpson DG, Sanders EH, et al. Release of tetracycline hydrochloride from electrospun poly (ethylene-co-vinylacetate, poly (lactic acid), and a blend. J Control Release 2002;81:57–64.
Kenawy R, Layman JM, Watkins JR, Bowlin GL, Matthews JA, Simpson DG, et al. Electrospinning of poly (ethylene-co-vinyl alcohol) fibers. Biomaterials 2003;24: 907–13.
Khil MS, Cha DI, Kim HY, Kim IS, Bhattarai N. Electrospun nanofibrous polyurethane membrane as wound dressing. J Biomed Mater Res B 2003;67:675–9.
Ki CS, Baek DH, Gang KD, Lee KH, Um IC, Park YH. Characterization of gelatin nanofiber prepared from gelatin-formic acid solution. Polymer 2005;46:5094–102.
Ki CS, Kim JW, Hyun JH, Lee KH, Hattori M, Rah DK, et al. Electrospun three dimensional silk fibroin nanofibrous scaffold. J Appl Polym Sci 2007;106:3922–8.
Kidoaki S, Kwon IK, Matsuda T. Mesoscopic spatial designs of nano and microfiber meshes for tissue-engineering matrix and scaffold based on newly devised multilayering and mixing electrospinning techniques. Biomaterials 2005;26:37–46.
Kim JS, Lee DS. Thermal properties of electrospun polyesters. Polym J 2000;32:616–8.
Kim TG, Park TG. Surface functionalized electrospun biodegradable nanofibers for immobilization of bioactive molecules. Biotechnol Prog 2006;22:1108–13.
Kim JS, Reneker DH. Mechanical properties of composites using ultrafine electrospun fibers. Polym Compos 1999;20:124–31.
Kim K, Yu M, Zong X, Chiu J, Fang D, Hsiao BS, et al. Control of degradation rate and hydrophilicity in electrospun non-woven poly (D, L-lactide) nanofiber scaffolds for biomedical applications. Biomaterials 2003;24:4977–85.
Kim K, Luu YK, Chang C, Fang D, Hsiao BS, Chu B, et al. Incorporation and controlled release of a hydrophilic antibiotic using poly(lactide-co-glycolide)-based electrospun nanofibrous scaffolds. J Control Release 2004;98:47–56.
Kim KH, Jeong L, Park HN, Shin SY, Park WH, Lee SC, et al. Biological efficacy of silk fibroin nanofiber membranes for guided bone regeneration. J Biotechnol 2005a;120: 327–39.
Kim B, Park H, Lee SH, Sigmund WM. Poly (acrylic acid) nanofibers by electrospinning. Mater Lett 2005b;59:829–32.
Kim BC, Nair S, Kim J, Kwak JH, Grate JW, Kim SH, et al. Preparation of biocatalytic nanofibers with high activity and stability via enzyme aggregate coating on polymer nanofibers. Nanotechnology 2005c;16:S382–8.
Klein E. Affinity membranes: a 10-year review. J Membr Sci 2000;179:1-27.
Ko F, Gogotsi Y, Ashraf A, Naguib N, Ye H, Yang G, et al. Electrospinning of continuous carbon nanotube-filled nanofiber yarns. Adv Mater 2003;15:1161–5.
Kobayashi H, Yokoyama Y, Takato T, Koyama H, Ichioka S. Spongiform structured materials and it's manufacturing methods. Japanese patent Application number 2007–103201.
Koski A, Yim K, Shivkumar S. Effect of molecular weight on fibrous PVA produced by electrospinning. Mater Lett 2004;58:493–7.
Kost J, Langer R. Responsive polymeric delivery systems. Adv Drug Deliv Rev 2001;46: 125–48.
Kuijpers AJ, Wachem PBV, Dalton PD, Van Luyn MJ, Plantinga JA, Engbers GH, et al. In vivo compatibility and degradation of crosslinked gelatin gels incorporated in knitted Dacron. J Biomed Mater Res 2000a;51:136–45.
Kuijpers AJ, Engbers GH, Krijgsveld J, Zaat SA, Dankert J, Feijen J. Cross-linking and characterisation of gelatin matrices for biomedical applications. J Biomater Sci Polym Ed 2000b;11:225–43.
Kumbar SG, Nukavarapu SP, James R, Hogan MV, Laurencin CT. Recent patents on electrospun biomedical nanostructures: an overview. Biomed Eng 2008;1: 68–78.
Kundu A, Kishore N. 1, 1, 1, 3, 3, 3-Hexafluoroisopropanol induced thermal unfolding and molten globule state of bovine alpha-lactalbumin: calorimetric and spectroscopic studies. Biopolymers 2004;73:405–20.
Kwon IK, Matsuda T. Co-electrospun nanofiber fabrics of poly (l-lactide-*co*-ε-caprolactone) with type I collagen or heparin. Biomacromolecules 2005;6:2096–105.
Lala NL, Ramaseshan R, Bojun L, Sundarrajan S, Barhate RS, Liu YJ, et al. Fabrication of nanofibers with antimicrobial functionality used as filters: protection against bacterial contaminants. Biotechnol Bioeng 2007;97:1357–65.
Langer R, Vacanti JP. Tissue Engineering. Science 1993;260:920–6.
Lannutti J, Reneker D, Ma T, Tomasko D, Farson D. Electrospinning for tissue engineering scaffolds. Mater Sci Eng C 2007;27:504–9.
Larrondo L, Manley RSJ. Electrostatic fiber spinning from polymer melts. I. experimental observations on fiber formation and properties. J Polym Sci, Polym Phys Ed 1981a;19:909–20.
Larrondo L, Manley RSJ. Electrostatic fiber spinning from polymer melts. II. examination of the flow field in an electrically driven jet. J Polym Sci, Polym Phys Ed 1981b;19:921–32.
Larrondo L, Manley RSJ. Electrostatic fiber spinning from polymer melts. III. Electrostatic deformation of a pendant drop of polymer melts. J Polym Sci, Polym Phys Ed 1981c;19:933–40.
Lee KH, Kim HY, La YM, Lee DR, Sung NH. Influence of a mixing solvent with tetrahydrofuran and N, N-dimethylformamide on electrospun poly (vinylchloride) nonwoven mats. J Polym Sci, B Polym Phys 2002a;40:2259–68.
Lee SH, Ku BC, Wang X, Samuelson LA, Kumar J. Design, synthesis and electrospinning of a novel fluorescent polymer for optical sensor applications. Mater Res Soc Symp Proc 2002b;708:403–8.
Lee KH, Kim HY, Bang HJ, Jung YH, Lee SG. The change of bead morphology formed on electrospun polystyrene fibres. Polymer 2003a;44:4029–34.
Lee KH, Kim HY, Khil MS, Ra YM, Lee DR. Characterization of nanostructured poly(e-caprolactone) nonwoven mats via electrospinning. Polymer 2003b;44: 1287–94.
Lee KH, Kim HY, Ryu YJ, Kim KW, Choi SW. Mechanical behavior of electrospun fiber mats of poly(vinyl chloride)/polyurethane polyblends. J Polym Sci, B Polym Phys 2003c;41:1256–62.
Lee JS, Choi KH, Ghim HD, Kim SS, Chun DH, Kim HY, et al. Role of molecular weight of a tactic poly (vinyl alcohol) (PVA) in the structure and properties of PVA nanofabric prepared by electrospinning. J Appl Polym Sci 2004;93:1638–46.
Lee YH, Lee JH, An IG, Kim C, Lee DS, Lee YK, et al. Electrospun dual-porosity structure and biodegradation morphology of montmorillonite reinforced PLLA nanocomposite scaffolds. Biomaterials 2005a;26:3165–72.
Lee KH, Ki CS, Baek DH, Kang GD, Ihm DW, Park YH. Application of electrospun silk fibroin nanofibers as an immobilization support of enzyme. Fibers Polym 2005b;6: 181–5.
Li D, Xia Y. Electrospinning of nanofibers: reinventing the wheel. Adv Mater 2004;16: 1151–70.
Li WJ, Laurencin CT, Caterson EJ, Tuan RS, Ko FK. Electrospun nanofibrous structure: a novel scaffold for tissue engineering. J Biomed Mater Res 2002;60:613–21.
Li WJ, Danielson KG, Alexander PG, Tuan RS. Biological response of chondrocytes cultured in three-dimensional nanofibrous poly (epsilon-caprolactone) scaffolds. J Biomed Mater Res 2003a;67A:1105–14.
Li D, Wang Y, Xia Y. Electrospinning of polymeric and ceramic nanofibers as uniaxially aligned arrays. Nano Lett 2003b;3:1167–71.
Li D, Wang Y, Xia Y. Electrospinning nanofibers as uniaxially aligned arrays and layer-by-layer stacked films. Adv Mater 2004;16:361–6.
Li M, Mondrinos MJ, Gandhi MR, Ko FK, Weiss AS, Lelkes PI. Electrospun protein fibers as matrices for tissue engineering. Biomaterials 2005a;26:5999–6008.
Li D, Ouyang G, McCann JT, Xia Y. Collecting electrospun nanofibers with patterned electrodes. Nano Lett 2005b;5:913–6.
Li J, He A, Zheng J, Han CC. Gelatin and gelatin-hyaluronic acid nanofibrous membranes produced by electrospinning of their aqueous solutions. Biomacromolecules 2006a;7:2243–7.
Li C, Vepari C, Jin HJ, Kim HJ, Kaplan DL. Electrospun silk-BMP-2 scaffolds for bone tissue engineering. Biomaterials 2006b;27:3115–24.
Li M, Guo Y, Wei Y, MacDiarmid AG, Lelkes PI. Electrospinning polyaniline-contained gelatin nanofibers for tissue engineering applications. Biomaterials 2006c;27: 2705–15.
Li SF, Chen JP, Wu WT. Electrospun polyacrylonitrile nanofibrous membranes for lipase immobilization. J Mol Catal, B Enzym 2007;47:117–24.
Liang D, Hsiao BS, Chu B. Functional electrospun nanofibrous scaffolds for biomedical applications. Adv Drug Deliv Rev 2007;59:1392–412.
Liu Y, He JH. Bubble electrospinning for mass production of nanofibers. Int J Nonlinear Sci Numer Simul 2007;8:393–6.
Liu HQ, Hsieh YL. Ultrafine fibrous cellulose membranes from electrospinning of cellulose acetate. J Polym Sci B Polym Phys 2002;40:2119–29.
Liu Y, Liu H, Qian J, Deng J, Yu T. Feature of an amperometric ferrocyanide-mediating H_2O_2 sensor for organic-phase assay based on regenerated silk fibroin as immobilization matrix for peroxidase. Electrochim Acta 1996;41:77–82.
Loscertales IG, Barrero A, Guerrero I, Cortijo R, Marquez M, Nancalvo AMG. Micro/ nano encapsulation via electrified co-axial liquid jet. Science 2002;295:1695–8.
Luu YK, Kim K, Hsiao BS, Chu B, Hadjiargyrou M. Development of a nanostructured DNA delivery scaffold via electrospinning of PLGA and PLA-PEG block copolymers. J Control Release 2003;89:341–53.
Lyons J, Ko F. Melt electrospinning of polymers: a review. Polym News 2005;30:1–9.
Lyons J, Li C, Ko F. Melt-electrospinning part I: processing parameters and geometric properties. Polymer 2004;45:7597–603.
Ma Z, Ramakrishna S. Electrospun regenerated cellulose nanofiber affinity membrane functionalized with protein A/G for IgG purification. J Membr Sci 2008;319:23–8.
Ma Z, Kotaki M, Inai R, Ramakrishna S. Potential of nanofiber matrix as tissue-engineering scaffolds. Tissue Eng 2005a;11:101–9.
Ma ZW, Kotaki M, Ramakrishna S. Electrospun cellulose nanofiber as affinity membrane. J Membr Sci 2005b;265:115–23.
Ma Z, He W, Yong T, Ramakrishna S. Grafting of gelatin on electrospun poly (caprolactone) nanofibers to improve endothelial cell spreading and proliferation and to control cell orientation. Tissue Eng 2005c;11:1149–58.
Martin GE, Cockshott ID, Fildes FJT. Fibrillar lining for prosthetic device. US patent 4044404, 1977.
Martin GE, Cockshott ID, Fildes FJT. Fibrillar Product. US Patent 4552707, 1985.
Martinek K, Klibanov AM, Goldmacher VS, Berezin IV. The principles of enzyme stabilization I. Increase in thermostability of enzymes covalently bound to a complementary surface of a polymer support in a multipoint fashion. Biochim Biophys Acta 1977;485:1-12.
Matthews JA, Wnek GE, Simpson DG, Bowlin GL. Electrospinning of collagen nanofibers. Biomacromolecules 2002;3:232–8.

Matthews JA, Boland ED, Wnek GE, Simpson DG, Bowlin GL. Electrospinning of collagen type II: a feasibility study. J Bioact Compat Polym 2003;18:125–34.
McCreery MJ. Topical Skin Protectants. US Patent 5, 607, 979, 1997.
Mckee MG, Wilkes GL, Colby RH, Long TE. Correlations of solution rheology with electrospun fiber formation of linear and branched polyesters. Macromolecules 2004;37:1760–7.
McKee MG, Layman JM, Cashion MP, Long TE. Phospholipid non-woven electrospin membranes. Science 2006;311:353–5.
Megelski S, Stephens JS, Chase DB, Rabolt JF. Micro-and nanostructured surface morphology on electrospun polymer fibers. Macromolecules 2002;35:8456–66.
Meinel L, Hofmann S, Karageorgiou V, Kirker-Head C, McCool J, Gronowicz G, et al. The inflammatory responses to silk films in vitro and *in vivo*. Biomaterials 2005;26: 147–55.
Min BM, Lee G, Kim SH, Nam YS, Lee TS, Park WH. Electrospinning of silk fibroin nanofibers and its effect on the adhesion and spreading of normal by human keratinocytes and fibroblasts *in vitro*. Biomaterials 2004a;25:1289–97.
Min BM, Jeong L, Nam YS, Kim JM, Kim JY, Park WH. Formation of silk fibroin matrices with different texture and its cellular response to normal human keratinocytes. Int J Biol Macromol 2004b;34:223–30.
Mit-uppatham C, Nithitanakul M, Supaphol P. Ultrafine electrospun polyamide-6 fibers: effect of solution conditions on morphology and average fiber diameter. Macromol Chem Phys 2004;205:2327–38.
Mo XM, Xu CY, Kotaki M, Ramakrishna S. Electrospun P (LLA-CL) nanofiber: a biomimetic extracellular matrix for smooth muscle cell and endothelial cell proliferation. Biomaterials 2004;25:1883–90.
Morton WJ. Method of dispersing fluids. US Patent Specification 705691, 1902.
Moses M, Hohman MM, Shin YM, Rutledge GC, Brenner MP. Electrospinning and electrically forced jets. I. Stability theory. Phys Fluids 2001;13:2201–20.
Nagapudi K, Brinkman WT, Leisen JE, Huang L, McMillan RA, Apkarian RP, et al. Photomediated solid-state cross-linking of an elastin-mimetic recombinant protein polymer. Macromolecules 2002;35:1730–7.
Nagura M, Yokota H, Ikeura M, Gotoh Y, Ohkoshi Y. Structures and physical properties of cross-linked gelatin fibers. Polym J 2002;34:761–6.
Nam J, Huang Y, Agarwal S, Lannutti J. Improved cellular infiltration in electrospun fiber via engineered porosity. Tissue Eng 2007;13:2249–57.
Naraghi M, Chasiotis I, Kahn H, Wen Y, Dzenis Y. Novel method for mechanical characterization of polymeric nanofibers. Rev Sci Instrum 2007;78:1–7.
Neal RA, McClugage III SG, Link MC, Sefcik LS, Ogle RC, Botchwey EA. Laminin nanofiber meshes that mimic morphological properties and bioactivity of basement membranes. Tissue Eng Part C 2008;15:11–21.
Nerem RM, Sambanis A. Tissue engineering: from biology to biological substitutes. Tissue Eng 1995;1:3-13.
Noh HK, Lee SW, Kim JM, Oh JE, Kim KH, Chung CP, et al. Electrospinning of chitin nanofibers: degradation behavior and cellular response to normal human keratinocytes and fibroblasts. Biomaterials 2006;27:3934–44.
Norris ID, Shaker MM, Ko FK, Macdiarmid AG. Electrostatic fabrication of ultrafine conducting fibers: polyaniline/polyethylene oxide blends. Synthetic Metals 2000;114: 109–14.
Ohgo K, Zhao C, Kobayashi M, Asakura T. Preperation of non- woven nanofibers for *Bombyx mori* silk, *Samia cythia ricini* silk and recombinant hybrid silk with electrospinnning method. Polymer 2003;44:841–6.
Ohkawa K, Kim H, Lee K, Yamamoto H. Electrospun non-woven fabrics of poly(e-caprolactone) and their biodegradation by pure cultures of soil filamentous fungi. Macromol Symp 2004a;216:301–6.
Ohkawa K, Cha D, Kim H, Nishida A, Yamamoto H. Electrospinning of chitosan. Macromol Rapid Commun 2004b;25:1600–5.
Ojha SS, Stevens DR, Stano K, Hoffman T, Clarke LI, Gorga RE. Characterization of electrical and mechanical properties for coaxial nanofibers with poly (ethylene oxide) (PEO) core and multiwalled carbon nanotube/PEO sheath. Macromolecules 2008;41:2509–13.
Onal S, Telefoncu A. Preparation and properties of β- galactosidase chemically attached to activated chitin. Artif Cells Blood Substit Biotechnol 2003;31:339–55.
Pa JH, Yu TL. Light scattering study of chitosan in acetic acid aqueous solutions. Macromol Chem Phys 2001;202:985–91.
Park SN, Lee HJ, Lee KH, Suh H. Biological characterization of EDC-crosslinked collagen-hyaluronic acid matrix in dermal tissue restoration. Biomaterials 2003;24: 1631–41.
Park WH, Jeong L, Yoo DI, Hudson S. Effect of chitosan on morphology and conformation of electrospun silk fibroin nanofibers. Polymer 2004;45:7151–7.
Park KE, Jung SY, Lee SJ, Min BM, Park WH. Biomimetic nanofibrous scaffolds: preparation and characterization of chitin/silk fibroin blend nanofibers. Int J Biol Macromol 2006;38:165–73.
Parry DAD, Craig AS. Collagen fibrils during development and maturation and their contribution to the mechanical attributes of connective tissue. In: Nimni ME, editor. Collagen, vol. 2. Boaca Raton, FL: CRC Press; 1988. p. 1-24.
Passaretti D, Silverman RP, Huang W, Kirchhoff CH, Ashiku S, Randolph MA, et al. Cultured chondrocytes produce injectable tissue-engineered cartilage in hydrogel polymer. Tissue Eng 2001;7:805–15.
Pavlov MP, Mano JF, Neves NM, Reis RL. Fibers and 3D mesh scaffolds from biodegradable starch based blends: production and characterization. Macromol Biosci 2004;4: 776–84.
Pawlowski KJ, Barnes CP, Boland ED, Wnek GE, Bowlin GL. Biomedical nanoscience: electrospinning basic concepts, applications, and classroom demonstration. Mater Res Soc Symp Proc 2004;827:17–28.
Pedicini A, Farris RJ. Mechanical behavior of electrospun polyurethane. Polymer 2003;44:6857–62.
Peretti GM, Randolph MA, Zaporojan V, Bonassar LJ, Xu JW, Fellers JC, et al. A biomechanical analysis of an engineered cell-scaffold implant for cartilage repair. Ann Plast Surg 2001;46:533–7.
Pham QP, Sharma U, Mikos AG. Electrospun poly (ε-caprolactone) microfiber and multilayer nanofiber/microfiber scaffolds: characterization of scaffolds and measurement of cellular infiltration. Biomacromolecules 2006;7:2796–805.
Pierschbacher MD, Ruoslahti E. Cell attachment activity of fibronectin can be duplicated by small synthetic fragments of the molecule. Nature 1984;309:30–3.
Pinchuk L, Martin JB, Maurin AA. Breast prostheses. US Patent 5376117, 1994.
Prestwich GD. Simplifying the extracellular matrix for 3-D cell culture and tissue engineering: a pragmatic approach. J Cell Biochem 2007;101:1370–83.
Ramakrishna S, Fujihara K, Teo WE, Yong T, Ma Z, Ramaseshan R. Electrospun nanofibers: solving global issues. Mater Today 2006;9:40–50.
Ramanathan K, Bangar MA, Yun M, Chen W, Myung NV, Mulchandani A. Bioaffinity sensing using biologically functionalized conducting-polymer nanowire. J Am Chem Soc 2005;127:496–7.
Reneker DH, Chun L. Nanometre diameters of polymer, produced by electrospinning. Nanotechnology 1996;7:216–23.
Reneker DH, Yarin AL. Electrospinning jets and polymer nanofibers. Polymer 2008;49: 2387–425.
Reneker DH, Yarin AL, Fong H, Koombhongse S. Bending instability of electrically charged liquid jets of polymer solutions in electrospinning. J Appl Phys 2000;87:4531–47.
Rho KS, Jeong L, Lee G, Seo BM, Park YJ, Hong SD, et al. Electrospinning of collagen nanofibers: effects on the behavior of normal human keratinocytes and early-stage wound healing. Biomaterials 2006;27:1452–61.
Riboldi SA, Sampaolesi M, Neuenschwander P, Cossu G, Mantero S. Electrospun degradable polyesterurethane membranes: potential scaffolds for skeletal muscle tissue engineering. Biomaterials 2005;26:4606–15.
Ryu YJ, Kim HY, Lee KH, Park HC, Lee DR. Transport properties of electrospun nylon 6 non-woven mats. Eur Polym J 2003;39:1883–9.
Saito N, Okada T, Horiuchi H, Murakami N, Takahashi J, Nawata M, et al. Biodegradable polymer as a cytokine delivery system for inducing bone formation. Nat Biotechnol 2001;19:332–5.
Sakurai K, Shibano T, Kimura K, Takahashi T, Gakkaishi S. Crystal structure of chitosan II. Molecular packing in unit cell of crystal. Sen-i Gakkaishi 1985;41:T361–8.
Sanders EH, Kloefkorn R, Bowlin GL, Simpson DG, Wnek GE. Two-phase electrospinning from a single electrified jet: microencapsulation of aqueous reservoirs in poly (ethylene-co-vinyl acetate) fibres. Macromolecules 2003;36:3803–5.
Schreuder-Gibson HL, Gibson P, Senecal K, Sennett M, Walker J, Yeomans W, et al. Protective textile materials based on electrospun nanofibers. J Adv Mater 2002;34: 44–55.
Senecal KJ, Ziegler DP, He J, Mosurkal R, Schreuder-Gibson H, Samuelson LA. Photoelectric response from nanofibrous membranes. Mater Res Soc Symp Proc 2002;708:285–9.
Shields KJ, Beckman MJ, Bowlin GL, Wayne JS. Mechanical properties and cellular proliferation of electrospun collagen type II. Tissue Eng 2004;10:1510–7.
Shin YM, Hohman MM, Brenner MP, Rutledge GC. Experimental characterization of electrospinning: the electrically forced jet and instabilities. Polymer 2001a;42:9955–67.
Shin YM, Hohman MM, Brenner MP, Rutledge GC. Electrospinning: a whipping fluid jet generates submicron polymer fibers. Appl Phys Lett 2001b;78:1149–51.
Shin M, Ishii O, Sueda T, Vacanti JP. Contractile cardiac grafts using a novel nanofibrous mesh. Biomaterials 2004a;25:3717–23.
Shin M, Yoshimoto H, Vacanti JP. In vivo bone tissue engineering using mesenchymal stem cells on a novel electrospun nanofibrous scaffold. Tissue Eng 2004b;10:33–41.
Shin MK, Kim SI, Kim SJ, Kim SK, Lee H, Spinks GM. Size-dependent elastic modulus of single electroactive polymer nanofibers. Appl Phys Lett 2006;89:1929–33.
Shu XZ, Liu Y, Palumbo FS, Luo Y, Prestwich GD. *In situ* crosslinkable hyaluronan hydrogels for tissue engineering. Biomaterials 2004;25:1339–48.
Sill TJ, Recum HAV. Electrospinning: applications in drug delivery and tissue engineering. Biomaterials 2008;29:1989–2006.
Silva GA, Czeisler C, Niece KL, Beniash E, Harrington DA, Kessler JA, et al. Selective differentiation of neural progenitor cells by high-epitope density nanofibers. Science 2004;303:1352–5.
Simons HL. Process and Apparatus for Producing Patterned Nonwoven Fabrics. US patent 3, 280, 229, 1966.
Smith LA, Ma PX. Nano-fibrous scaffolds for tissue engineering. Colloid Surf B 2004;39: 125–31.
Smith D, Reneker D, McManus A, Schreuder-Gibson H, Mello C, Sennet M, et al. Electrospun Fibers and an Apparatus Therefore. PCT International Application No: PCT/US00/27776, 2001.
Son WK, Youk JH, Park WH. Preparation of ultrafine oxidized cellulose mats via electrospinning. Biomacromolecules 2004a;5:197–201.
Son WK, Youk JH, Lee TS, Park WH. Electrospinning of ultrafine cellulose acetate fibers: studies of a new solvent system and deacetylation of ultrafine cellulose acetate fibers. J Polym Sci, B Polym Phys 2004b;42:5-11.
Son WK, Youk JH, Lee TS, Park WH. The effects of solution properties and polyelectrolyte on electrospinning of ultrafine poly (ethylene oxide) fibers. Polymer 2004c;45:2959–66.
Songchotikunpan P, Tattiyakul J, Supaphol P. Extraction and electrospinning of gelatin from fish skin. Int J Biol Macromol 2008;42:247–55.
Spasova M, Paneva D, Manolova N, Radenkov P, Rashkov I. Electrospun chitosan coated fibers of poly(L-lactide) and poly(L-lactide)/poly(ethyleneglycol):preparation and characterization. Macromol Biosci 2008;8:153–62.
Srinivasan G, Reneker DH. Structure and morphology of small diameter electrospun Aramid fibers. Polymer Int 1995;36:195–201.
Stankus JJ, Guan J, Wagner WR. Fabrication of biodegradable elastomeric scaffolds with sub-micron morphologies. J Biomed Mater Res 2004;70A:603–14.

Stankus JJ, Guan J, Fujimoto K, Wagner WR. Microintegrating smooth muscle cells into a biodegradable, elastomeric fiber matrix. Biomaterials 2006;27:735–44.
Stenoien MD, Drasler WJ, Scott RJ, Jenson ML. Silicone Composite Vascular Graft. US Patent 5866217, 1999.
Stillwell CR. Characterization of pore structure in filter cartridges. Adv Filtr Sep Technol 1996;10:151–6.
Stitzel J, Pawlowski K, Wnek G, Simpson D, Bowlin G. Arterial smooth muscle cell proliferation on a novel biomimicking, biodegradable vascular graft scaffold. J Biomater Appl 2001;16:22–33.
Subbiah T, Bhat GS, Tock RW, Parameswaran S, Ramkumar SS. Electrospinning of nanofibers. J Appl Polym Sci 2005;96:557–69.
Sukigara S, Gandhi M, Ayutsede J, Micklus M, Ko F. Regeneration of *Bombyx mori* silk by electrospinning—part 1:processing parameters and geometric properties. Polymer 2003;44:5721–7.
Sukigara S, Gandhi M, Ayutsede J, Micklus M, Ko F. Regeneration of *Bombyx mori* silk by electrospinning. Part 2. Process optimization and empirical modeling using response surface methodology. Polymer 2004;45:3701–8.
Sun ZC, Zussman E, Yarin AL, Wendorff JH, Greiner A. Compound core-shell polymer nanofibers by co-electrospinning. Adv Mater 2003;15:1929–32.
Sun T, Mai S, Norton D, Haycock JW, Ryan S, Mac Neil AJ. Self organization of skin cells in three dimensional electrospun polystyrene scaffolds. Tissue Eng 2005;11:1023–33.
Sun L, Han RPS, Wang J, Lim CT. Modeling the size-dependent elastic properties of polymeric nanofibers. Nanotechnology 2008;19:1–8.
Sundaray B, Subramanian V, Natarajan TS, Xiang RZ, Chang CC, Fann WS. Electrospinning of continuous aligned polymer fibers. Appl Phys Lett 2004;84:1222–4.
Tan EPS, Lim CT. Mechanical characterization of nanofibers — a review. Compos Sci Technol 2006;66:1102–11.
Tan EPS, Ng SY, Lim CT. Tensile testing of a single ultrafine polymeric fiber. Biomaterials 2005a;26:1453–6.
Tan SH, Inai R, Kotaki M, Ramakrishna S. Systematic parameter study for ultra-fine fiber fabrication via electrospinning process. Polymer 2005b;46:6128–34.
Taylor GI. Electrically Driven Jets. Proc R Soc Lond, A Math Phys Sci, (1934–1990), 1969; 313, 453-75.
Teeters MA, Conrardy SE, Thomas BL, Root TW, Lightfoot EN. Adsorptive membrane chromatography for purification of plasmid DNA. J Chromatogr A 2003;989:165–73.
Telemeco TA, Ayres C, Bowlin GL, Wnek GE, Boland ED, Cohen N, et al. Regulation of cellular infiltration into tissue engineering scaffolds composed of submicron diameter fibrils produced by electrospinning. Acta Biomater 2005;1:377–85.
Teo WE, Ramakrishna S. A review on electrospinning design and nanofiber assemblies. Nanotechnology 2006;17:89-106.
Theron SA, Yarin AL, Zussman E, Kroll E. Multiple jets in electrospinning: experiment and modeling. Polymer 2005;46:2889–99.
Thomas S. Wound management and dressings. Pharm Presse 1990;1:37–57.
Titoba E, Belavtseva E, Gamzazade A, Sklyar A, Pavlova S, Rogozhin S. Investigation of the structure formation of chitosan in solutions by transmission electron microscopy. Acta Polym 1986;37:121–4.
Tomas J, Kula MR. Membrane chromatography—an integrative concept in the downstream processing of proteins. Biotechnol Prog 1995;11:357–67.
Tomaszewski W, Szadkowski M. Investigation of electrospinning with the use of a multi-jet electrospinning head. Fibres Text East Eur 2005;13:22–6.
Tsaia PP, Schreuder-Gibson H, Gibson P. Different electrostatic methods for making electret filters. J Electrost 2002;54:333–41.
Tuan RS, Boland G, Tuli R. Adult mesenchymal stem cells and cell-based tissue engineering. Arthritis Res Ther 2003;5:32–45.
Um IC, Fang DF, Hsiao BS, Okamoto A, Chu B. Electro-spinning and electro-blowing of hyaluronic acid. Biomacromolecules 2004;5:1428–36.
Underwood S, Afoke A, Brown RA, MacLeod AJ, Dunnill P. The physical properties of a fibrillar fibronectin–fibrinogen material with potential use in tissue engineering. Bioprocess Eng 1999;20:239–48.
Underwood S, Afoke A, Brown RA, MacLeod AJ, Shamlou PA, Dunnill P. Wet extrusion of fibronectin–fibrinogen cables for application in tissue engineering. Biotechnol Bioeng 2001;73:295–305.
Varabhas JS, Chase GG, Reneker DH. Electrospun nanofibers from a porous hollow tube. Polymer 2008;49:4226–9.
Veleirinho B, Rei MF, Lopes-da-Silva JA. Solvent and concentration effects on the properties of electrospun poly (ethylene terephthalate) nanofiber mats. J Polym Sci, B Polym Phys 2008;46:460–71.
Venugopal J, Ramakrishna S. Biocompatible nanofiber matrices for the engineering of a dermal substitute for skin regeneration. Tissue Eng 2005;11:847–54.
Verreck G, Chun I, Peeters J, Rosenblatt J, Brewster ME. Preparation and characterization of nanofibers containing amorphous drug dispersions generated by electrostatic spinning. Pharm Res 2003;20:810–7.
Vonnegut B, Newbauer RL. Production of monodisperse liquid particles by electrical atomization. J Colloid Sci 1952;7:616–22.
Wang Y, Hsieh YL. Immobilization of lipase enzyme in polyvinyl alcohol (PVA) nanofibrous membranes. J Membr Sci 2008;309:73–81.
Wang P, Dai S, Waezsada SD, Tsao A, Davison BH. Enzyme stabilization by covalent binding in nanoporous sol–gel glass for nonaqueous biocatalysis. Biotechnol Bioeng 2001;74:249–55.
Wang X, Drew C, Lee SH, Senecal KJ, Kumar J, Samuelson LA. Electrospun nanofibrous membranes for highly sensitive optical sensors. Nano Lett 2002;2:1273–5.
Wang Y, Serrano S, Santiago-Aviles JJ. Raman characterization of carbon nanofibers prepared using electrospinning. Synthetic Metals 2003;138:423–7.
Wang X, Kim YG, Drew C, Ku BC, Kumar J, Samuelson LA. Electrostatic assembly of conjugated polymer thin layers on electrospun nanofibrous membranes for biosensors. Nano Lett 2004;4:331–4.
Wang M, Hsieh AJ, Rutledge GC. Electrospinning of poly (MMA-co-MAA) copolymers and their layered silicate nanocomposites for improved thermal properties. Polymer 2005a;46:3407–18.
Wang X, Um IC, Fang D, Okamoto A, Hsiao BS, Chu B. Formation of water-resistant hyaluronic acid nanofibers by blowing-assisted electro-spinning and non-toxic post treatments. Polymer 2005b;46:4853–67.
Wang H, Zhang YP, Shao HL, Hu XC. Structure of silk fibroin fibers made by an electrospinning process from a silk fibroin aqueous solution. J Appl Polym Sci 2006;101: 961–8.
Wannatong L, Sirivat A, Supaphol P. Effects of solvents on electrospun polymeric fibers: preliminary study on polystyrene. Polym Int 2004;53:1851–9.
Wayne JS, Mcdowell CL, Shields KJ, Tuan RS. *In vivo* response of polylactic acid-alginate scaffolds and bone marrow-derived cells for cartilage tissue engineering. Tissue Eng 2005;11:953–63.
Welle A, Kroger M, Doring M, Niederer K, Pindel E, Chronakis S. Electrospun aliphatic polycarbonates as tailored tissue scaffold materials. Biomaterials 2007;28:2211–9.
Wenger MPE, Bozec L, Horton MA, Mesquida P. Mechanical properties of collagen fibrils. Biophys J 2007;93:1255–63.
Wente VA. Superfine thermoplastic fibers. Ind Eng Chem 1956;48:1342–6.
Wnek GE, Carr ME, Simpson DG, Bowlin GL. Electrospinning of nanofibers fibrinogen structures. Nano Lett 2003;3:213–6.
Wu Y, He JH, Xu L, Yu JY. Electrospinning drug-loaded poly (Butylenes Succinate-co-bytylene Terephthalate) (PBST) with acetylsalicylic acid (aspirin). Int J Electrospun Nanofibers Appl 2007;1:1–6.
Xie JB, Hsieh YL. Ultra-high surface fibrous membranes from electrospinning of natural proteins: casein and lipase enzyme. J Mater Sci 2003;38:2125–33.
Xu CY, Inai R, Kotaki M, Ramakrishna S. Aligned biodegradable nanofibrous structure: a potential scaffold for blood vessel engineering. Biomaterials 2004;25:877–86.
Yamamoto M, Ikada Y, Tabata Y. Controlled release of growth factors based on biodegradation of gelatin hydrogel. J Biomater Sci, Polym Ed 2001;12:77–88.
Yang H, Bitzer M, Etzel MR. Analysis of protein purification using ion-exchange membranes. Ind Eng Chem Res 1999;38:4044–50.
Yang H, Viera C, Fischer J, Etzel MR. Purification of a large protein using ion-exchange membranes. Ind Eng Chem Res 2002;41:1597–602.
Yang F, Murugan R, Ramakrishna S, Wang X, Ma YX, Wang S. Fabrication of nano-structured porous PLLA scaffold intended for nerve tissue engineering. Biomaterials 2004a;25:1891–900.
Yang F, Xu CY, Kotaki M, Wang S, Ramakrishna S. Characterization of neural stem cells on electrospun poly (L-lactic acid) nanofibrous scaffold. J Biomater Sci Polym Ed 2004b;15:1483–97.
Yang Q, Li Z, Hong Y, Zhao Y, Qiu S, Wang C, et al. Influence of solvents on the formation of ultrathin uniform poly (vinyl pyrrolidone) nanofibers with electrospinning. J Polym Sci, B Polym Phys 2004c;42:3721–6.
Yang YM, Wang JW, Tan RX. Immobilization of glucose oxidase on chitosan–SiO2 gel. Enzyme Microb Technol 2004d;34:126–31.
Yang F, Murugan R, Wang S, Ramakrishna S. Electrospinning of nano/micro scale poly (L-lactic acid) aligned fibers and their potential in neural tissue engineering. Biomaterials 2005;26:2603–10.
Yang D, Li Y, Nie J. Preparation of gelatin/PVA nanofibers and their potential application in controlled release of drugs. Carbohydr Polym 2007;69:538–43.
Yang L, Fitie CFC, Werf KOV, Bennink ML, Dijkstra PJ, Feijen J. Mechanical properties of single electrospun collagen type I fibers. Biomaterials 2008;29:955–62.
Yao CH, Liu BS, Hsu SH, Chen YS, Tsai CC. Biocompatibility and biodegradation of a bone composite containing tricalcium phosphate and genipin crosslinked gelatin. J Biomed Mater Res 2004;69A:709–17.
Yarin AL, Zussman E. Upward needleless electrospinning of multiple nanofibers. Polymer 2004;45:2977–80.
Yarin AL, Koombhongse S, Reneker DH. Bending instability in electrospinning of nanofibers. J Appl Phys 2001;89:3018–26.
Ye Q, Zund G, Benedikt P, Jockenhoevel S, Hoerstrup SP, Sakyama S, et al. Fibrin gel as a three dimensional matrix in cardiovascular tissue engineering. Eur J Cardiothorac Surg 2000;17:587–91.
Ye P, Xu ZK, Che AF, Wu J, Seta P. Chitosan-tethered poly (acrylonitrile-co-maleic acid) hollow fiber membrane for lipase immobilization. Biomaterials 2005;26:6394–403.
Ye P, Xu ZK, Wu J, Innocent C, Seta P. Nanofibrous membranes containing reactive groups: electrospinning from poly(acrylonitrile-co-maleic acid) for lipase immobilization. Macromolecules 2006;39:1041–5.
Yokoyama Y, Hattori S, Yoshikawa C, Yasuda Y, Koyama H, Takato T, et al. Novel wet electrospinning system for fabrication of spongiform nanofiber 3-dimensional fabric. Mater Lett 2009;63:754–6.
Yoo HS, Lee EA, Yoon JJ, Park TG. Hyaluronic acid modified biodegradable scaffolds for cartilage tissue engineering. Biomaterials 2005;26:1925–33.
Yordem OS, Papila M, Menceloğlu YZ. Effects of electrospinning parameters on polyacrylonitrile nanofiber diameter: an investigation by response surface methodology. Mater Des 2008;29:34–44.
Yoshimoto H, Shin YM, Terai H, Vacanti JP. A biodegradable nanofiber scaffold by electrospinning and its potential for bone tissue engineering. Biomaterials 2003;24: 2077–82.
Yuan XY, Zhang YY, Dong CH, Sheng J. Morphology of ultrafine polysulfone fibers prepared by electrospinning. Polym Int 2004;53:1704–10.
Yun YH, Goetz DJ, Yellen P, Chen W. Hyaluronan microspheres for sustained gene delivery and site specific targeting. Biomaterials 2004;25:147–57.
Yuya PA, Wen Y, Turner JA, Dzenis YA, Li Z. Determination of Young's modulus of individual electrospun nanofibers by microcantilever vibration method. Appl Phys Lett 2007;90:1–3.
Zarkoob S, Reneker DH, Eby RK, Hudson SD, Ertley D, Adams WW. Polym Preprints 1998;39:244–5.

Zarkoob S, Eby RK, Reneker DH, Hudson SD, Ertley D, Adams WW. Structure and morphology of electrospun silk nanofibers. Polymer 2004;45:3973–7.
Zeleny J. The electrical discharge from liquid points, and a hydrostatic method of measuring the electric intensity at their surfaces. Phys Rev 1914;3:69–91.
Zeng J, Chen X, Xu X, Liang Q, Bian X, Yang L, et al. Ultrafine fibers electrospun from biodegradable polymers. J Appl Polym Sci 2003a;89:1085–92.
Zeng J, Xu X, Chen X, Liang Q, Bian X, Yang X, et al. Biodegradable electrospun fibers for drug delivery. J Control Release 2003b;92:227–31.
Zeng J, Hou H, Wendorff JH, Greiner A. Photo-induced solid-state crosslinking of electrospun poly(vinyl alcohol) fibers. Macromol Rapid Commun 2005;26:1557–62.
Zeugolis DI, Khew ST, Yew ESY, Ekaputra AK, Tong YW, Yung LYL, et al. Electro-spinning of pure collagen nano-fibres — just an expensive way to make gelatin? Biomaterials 2008;29:2293–305.
Zhang YQ. Natural silk fibroin as a support for enzyme immobilization. Biotechnol Adv 1998;16:961–71.
Zhang YQ, Zhu J, Gu RA. Improved biosensor for glucose based on glucose oxidase-immobilized silk fibroin membrane. Appl Biochem Biotechnol 1998;75:215–33.
Zhang Y, Qian J, Ke Z, Zhu X, Bi H, Nie K. Viscometric study of poly (vinyl chloride)/poly (vinyl acetate) blends in various solvents. Eur Polym J 2002;38:333–7.
Zhang Y, Ouyang H, Lim CT, Ramakrishna S, Huang ZM. Electrospinning of gelatin fibers and gelatin/PCL composite fibrous scaffolds. J Biomed Mater Res B Appl Biomater 2005a;72:156–65.
Zhang C, Yuan X, Wu L, Han Y, Sheng J. Study on morphology of electrospun poly (vinyl alcohol) mats. Eur Polym J 2005b;41:423–32.
Zhang YZ, Venugopal J, Huang ZM, Lim CT, Ramakrishna S. Characterization of the surface biocompatibility of the electrospun PCL-collagen nanofibers using fibroblasts. Biomacromolecules 2005c;6:2583–9.
Zhang YZ, Venugopal J, Huang ZM, Lim CT, Ramakrishna S. Crosslinking of the electrospun gelatin nanofibers. Polymer 2006;47:2911–7.
Zhang X, Baughman CB, Kaplan DL. In vitro evaluation of electrospun silk fibroin scaffolds for vascular cell growth. Biomaterials 2008a;29:2217–27.
Zhang L, Menkhaus TJ, Fong H. Fabrication and bioseparation studies of adsorptive membranes/felts made from electrospun cellulose acetate nanofibers. J Membr Sci 2008b;319:176–84.
Zhao C, Tao J, Masuda H, Kishore R, Asakura T. Structural characterization and artificial fiber formation of *Bombyx mori* silk fibroin in hexafluoro-iso-propanol solvent system. Biopolymers 2003;69:253–9.
Zhao ZZ, Li JQ, Yuan XY, Li X, Zhang YY, Sheng J. Preparation and properties of electrospun poly (vinylidene fluoride) membranes. J Appl Polym Sci 2005;97:466–74.
Zhmayev E, Zhou H, Joo YL. Modeling of non-isothermal polymer jets in melt electrospinning. J Non-Newtonian Fluid Mech 2008;153:95-108.
Zhong S, Teo WE, Zhu X, Beuerman R, Ramakrishna S, Yung LY. Formation of collagen-glycosaminoglycan blended nanofibrous scaffolds and their biological properties. Biomacromolecules 2005;6:2998–3004.
Zhong S, Teo WE, Zhu X, Beuerman RW, Ramakrishna S, Yung LYL. An aligned nanofibrous collagen scaffold by electrospinning and its effects on in vitro fibroblast culture. J Biomed Mater Res A 2006;79A:456–63.
Zhou H, Green TB, Joo YL. The thermal effects on electrospinning of polylactic acid melts. Polymer 2006;47:7497–505.
Zong X, Kim K, Fang D, Ran S, Hsiao BS, Chu B. Structure and process relationship of electrospun bioadsorbable nanofiber membrane. Polymer 2002a;439:4403–12.
Zong X, Fang D, Kim K, Ran S, Hsiao BS, Chu B, et al. Nonwoven nanofiber membranes of poly(lactide) and poly (glycolide-co-lactide) via electrospinning and application for antiadhesions. Polym. Preprints-Am Chem Soc Div Polym Chem 2002b;43:659–60.
Zong X, Ran S, Fang D, Hsiao BS, Chu B. Control of structure, morphology and property in electrospun poly (glycolide-co-lactide) non-woven membranes via post-draw treatments. Polymer 2003;44:4959–67.
Zong XH, Bien H, Chung CY, Yin LH, Fang DF, Hsiao BS, et al. Electrospun fine-textured scaffolds for heart tissue constructs. Biomaterials 2005;26:5330–8.
Zuo WW, Zhu MF, Yang W, Yu H, Chen YM, Zhang Y. Experimental study on relationship between jet instability and formation of beaded fibers during electrospinning. Polym Eng Sci 2005;45:704–9.
Zussman E, Yarin AL, Weihs D. A micro-aerodynamic decelerator based on permeable surfaces of nanofiber mats. Exp Fluids 2002;33:315–20.
Zussman E, Theron A, Yarin AL. Formation of nanofiber crossbars in electrospinning. Appl Phys Lett 2003;82:973–5.