



# Nanofiber technology: current status and emerging developments



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## ABSTRACT

Nanofibers have emerged as exciting one-dimensional nanomaterials for a broad spectrum of research and commercial applications owing to their unique physicochemical properties and characteristics. As a class of nanomaterials with cross-sectional diameters ranging from tens to hundreds of nanometers, nanofibers possess extremely high specific surface area and surface area-to-volume ratio. They are capable of forming networks of highly porous mesh with remarkable interconnectivity between their pores, making them an attractive choice for a host of advanced applications. In fact, the significant impact of nanofiber technology can be traced from the wide range of fundamental materials that can be used for the synthesis of nanofibers. These include natural polymers, synthetic polymers, carbon-based materials, semiconducting materials, and composite materials. Correspondingly, the emerging proof-of-concept applications of nanofibers spanning several important areas have been rapidly reported. This Review explores the current status and up-and-coming development of nanofiber technology, with an emphasis on its syntheses and applications. First, we highlight the current and emerging strategies used in synthesizing nanofibers. We briefly introduce the various established nanofiber synthesis techniques, especially the electrospinning method. We then focus on the emerging nanofiber synthesis strategies, such as solution blow spinning, centrifugal jet spinning, and electrohydrodynamic direct writing. Next, we discuss the emerging applications of nanofiber technology in various fields, specifically in three important areas of energy generation and storage, water treatment and environmental remediation, and healthcare and biomedical engineering. Despite all these advancements, there are still challenges to be addressed and overcome for nanofiber technology to move towards maturation. Nevertheless, we envision that with further progress in the development of nanofiber synthesis strategies and identification of “killer” applications of nanofibers, nanofiber technology will mature and move beyond its current state towards commercial realization and applications.

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## 1. Introduction

The world of nanomaterials comprises a wide range of intriguing materials with outstanding physical and chemical properties and characteristics. These materials include zero-dimensional nanoparticles or quantum dots, one-dimensional nanowires, nanorods, nanofibers, and nanotubes, and two-dimensional nanosheets [1–3]. Widely regarded as nanomaterials with great potential applications, nanofibers stand out among the rest of the nanomaterials. One of the most striking features of nanofibers is their exceptionally high surface area-to-volume ratio and high porosity, making them a robust and attractive candidate for many advanced applications. In fact, the real testament to the importance of nanofibers can be witnessed from the many building blocks from which they can be synthesized to the range of applications in which they have been demonstrated to have significant impact. To date, nanofibers have been prepared from an assortment of materials, such as natural polymers [4], synthetic polymers [5,6], carbon-based nanomaterials [7], semiconducting nanomaterials [8,9], and composite nanomaterials [10–16]. Along with the rapid progress in the synthesis and characterization of nanofibers over the past few years, tremendous efforts have been focused on exploring the potential functional applications of nanofibers, including energy generation and storage, water and environmental treatment, and healthcare and biomedical engineering.

Here, we provide a review on the current status, challenges, and emerging development of nanofiber technology. In contrast to several excellent reviews that have detailed specific nanofiber synthesis techniques, particularly electrospinning, for certain applications, either in electronics, photonics, or regenerative medicine [17–19], this article aims to provide a broad overview of the various emerging nanofiber synthesis techniques coupled with their applications spanning three major themes of energy, water and environment, and healthcare, over the last several years. We start with an introduction to the current and emerging nanofiber fabrication techniques. This will be followed by discussion on the applications of nanofiber technology over a broad spectrum of areas encompassing energy generation and storage, water and environmental treatment, and healthcare and biomedical engineering (Fig. 1). We then present our perspectives and outlook on the current challenges facing the development and applications of nanofiber technology and highlight numerous future research directions in this field. An important question that we seek to address here is, with the potential it possesses, how

nanofiber technology can move from its current state in terms of fabrications and applications, to commercialization and implementation in everyday lives.

## 2. Current strategies for nanofiber fabrication

Of all the current strategies available for synthesizing one-dimensional nanofibers, electrospinning is one of the most established and widely adopted techniques [20–23]. In general, the electrospinning set-up consists of a syringe with a nozzle, an electric field source, a counter electrode or grounded target, and a pump. The electrospinning process is based on the principle of electrostatics in which the electrostatic repulsion forces in a high electrical field are used for nanofiber synthesis. The solution to be electrospun is held in a syringe nozzle and a large electrical field is generated between the nozzle and counter electrode. As the solution is ejected, the solution droplet at the nozzle adopts a cone-shaped deformation due to the potential difference between the nozzle and the grounded target. As the charged jet accelerates towards the counter electrode, the solvent in the solution evaporates, leading to the formation of solid continuous nanofibers on the grounded target. The physical properties of the electrospun nanofibers are heavily dependent on a multitude of parameters, such as solution properties (e.g., conductivity, viscoelasticity, and surface tension), environmental factors (e.g., processing temperature and humidity), and technical variables (e.g., tip-counter electrode distance, applied electrical potential, and flow rate). In fact, a wide range of fibrous nanostructures have been successfully prepared using electrospinning. For example, more recently, multifunctional colloidal polymer nanofibers have been prepared by electrospinning the aqueous blends of poly(vinyl alcohol-co-vinyl acetate)/octadecyl amine-montmorillonite (PVA/ODA-MMT) matrix nanocomposite and poly(maleic acid-*alt*-acrylic acid) (poly(Mac-*alt*-AA) copolymers [24].

Besides the conventional electrospinning technique, several variations of this method have been developed lately. These include the multineedle, needleless, and co-electrospinning or co-axial electrospinning. The multineedle and needleless electrospinning techniques are utilized to enhance the productivity of the conventional electrospinning. The co-axial electrospinning, on the other hand, is developed to synthesize core-shell and multilayer composite nanofibrous structures with additional functionalities and improved quality. In co-axial electrospinning, two distinct

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