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NANOFIBER PRODUCTION [REVIEW]

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Abstract: *Nanofibers are very thin fibers having diameters lower than 100 nm and their lengths might be as long as possible within production limits. The large surface area of nanofibers gives opportunity to functionalize them. Nanofibers have several applications including both applications for industrial production in many sectors and for research studies. Nanofibers find applications in energy devices such as solar cells, fuel cells and nanogenarators; in filtration applications (such as water/oil filtration, fine particle filtration, aerosol filtration, air filtration, nanoparticle filtration) and in several medical applications including antibacterial efficacy, wound healing, drug delivery and scaffolds for tissue engineering.*
There are several methods to produce nanofibers: Electrospinning, self assembly, phase separation, bacterial cellulose, templating, drawing, extraction, vapor-phase polymerization, kinetically controlled solution synthesis, conventional chemical polymerization for anyline. Electrospinning is the most widely used method to produce nanofibers.In electrospinning, a high electric field, which is in kilovolts, is applied to a polymer solution. The polymer solution is drawn from a syringe to a collector surface.Electrospinning requires usage of appropriate solvent, removal of evaporating solvent, an adequate power supply to overcome the viscosity and surface tension of the polymer solution; while, jet instability and jet control remain as challenges in electrospinning. Nanofiber production methods possess some disadvantages as: higher cost compared to conventional fiber production methods, health hazards such as inhale risk of nanofibers during production and keeping the environment safe from evaporating solvents used during nanofiber production. Up to date, many researches have been conducted on nanofibers and electrospinning; still, more controllable, more cost effective, more environmentally friendly and safer methods are of essential importance to future applications of nanofibers.

Key words: *Nanofibers, nanofibrous mats, nanotechnology, electrospinning, functionalization.*

1. INTRODUCTION

As nanotechnology refers to the study of materials, structures and devices having at least one dimension equal to or less than 100 nm, nanofibers are very thin fibers having diameters lower than 100 nm [1].

The root of electrospinning stems from studies of 1600s. William Gilbert studied the electrostatic attraction of a liquid in 1600, Schönbein produced nitrated cellulose in 1846; and in 1887, C.V. Boys published a paper on nanofiber production [2]. The first electrospinning patent was issued by John Francis Cooley in 1900 [3]. John Zeleny studied the fluid behavior under electrostatic forces in 1914 [4]; Zeleny's study opened a path for mathematical modelling studies of electrospun nanofibers. In 1934, Formhals took his first patent on electrospinning. In 1938, Rozenblum and Petryanov-Sokolov produced electrospun fibers. Between 1931 and 1944, Anton Formhals got more than 20 patents for electrospinning [2-4]. Between 1964 and 1969, Sir Geoffrey Ingram Taylor studied the cone of polymer fluid under electrostatic forces, those mathematical models led to this cone be named as 'Taylor cone' after him [2, 5, 6].

Since 2000s nanofiber research has shown a huge increase in scientific studies. We searched for publications about nanofibers using Web of Science search system with keys as 'electrospinning' or 'nanofiber' or 'nanofibrous' and the results of the search are given in Table 1 and the graph for nanofiber publications for years 1975-2016 is shown in Figure 1.

Table 1: *The number of published papers about nanofibers since 1975 (search done using Web of Science)*

year	Number of papers published	year	Number of papers published	year	Number of papers published	year	Number of papers published	year	Number of papers published
1975-1992	0	1997	5	2002	127	2007	594	2012	1774
1993	1	1998	13	2003	230	2008	869	2013	3111
1994	0	1999	17	2004	210	2009	989	2014	3580
1995	4	2000	23	2005	283	2010	1211	2015	3709
1996	3	2001	66	2006	453	2011	1542	2016	1001 *

*: until the 18th April of 2016

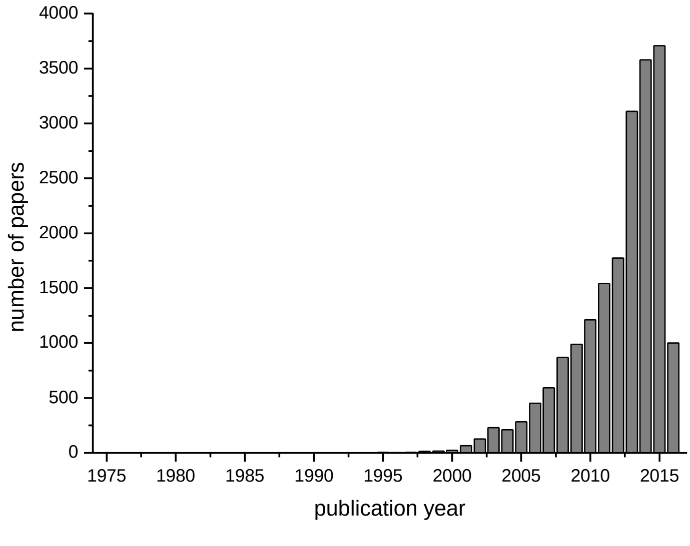


Fig. 1: *The annual number of published papers about nanofibers since 1975 (untill April 18 th of 2016)*

2. APPLICATIONS OF NANOFIBERS

The first commercial application of nanofibers dates back to 1930s indeed. The Soviet Union kept nanofiber studies secret and Petryanov successfully produced an electrospun filter named 'Filter of Petryanov' used for nuclear protection too; those filters were being mass produced in the Soviet Union [7, 8].

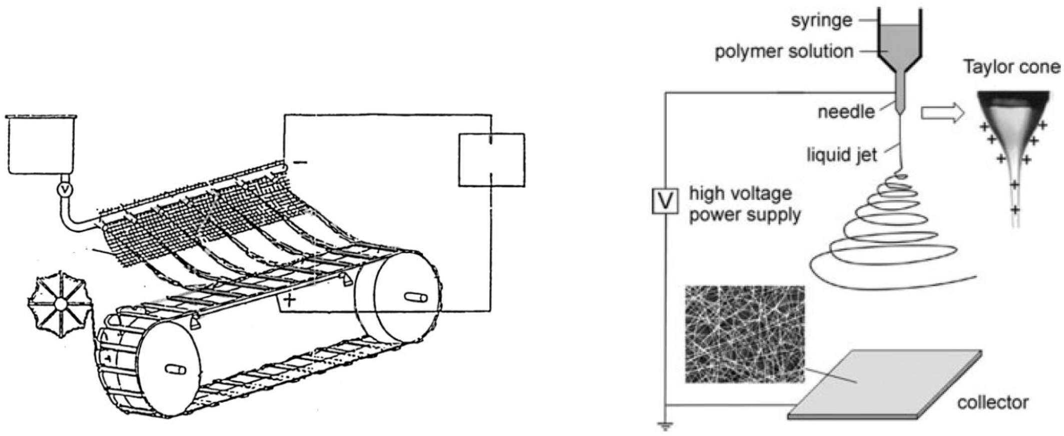
Nanofibers have several applications including both applications for industrial production in many sectors [31] and for research studies. Nanofibers find applications in energy devices such as solar cells, fuel cells and nanogenarators [9]; in filtration applications such as water/oil filtration [10, 11], fine particle filtration [12], aerosol filtration [13], air filtration [14], nanoparticle filtration [15] and in several medical applications including antibacterial efficacy [16], wound healing [17-21], drug delivery [22] and scaffolds for tissue engineering [23].

3. PRODUCTION OF NANOFIBERS

There are several methods to produce nanofibers: Electrospinning, self assembly, phase separation, bacterial cellulose, templating, drawing, extraction, vapor-phase polymerization, kinetically controlled solution synthesis, conventional chemical polymerization for anyline [24].

Nanofiber production methods possess some disadvantages as: higher cost compared to conventional fiber production methods, health hazards such as inhale risk of nanofibers during production and keeping the environment safe from evaporating solvents used during nanofiber production [1, 25].

In electrospinning, a high electric field, which is in kilovolts, is applied to a polymer solution. The polymer solution is drawn from a syringe to a collector surface [6]. The schematic for Formhals' 1934 patent and a modern schematic for electrospinning equipment are given in Figure 2a [26] and Figure 2b respectively [6].



(a) *(b)*

Fig. 2: ***(a)*** *The schematic in the 1934 patent of Formhals for electrospinning [26],* ***(b)*** *A schematic for a modern version of electrospinning equipment [6]*

There are many parameters affecting electrospinning such as process and system parameters (electric voltage, flow rate of polymer fluid, concentration of polymer solution, viscosity of solution, spinning distance between nozzle and collector, relaxation time, molecular weight, chemistry of polymer used); nozzle and set-up configuration (single nozzle, multiple nozzle, side by side nozzle, co-axial nozzle, aligned set-up, horizontal set-up); ambient parameters (temperature, humidity, air velocity) [2, 27].

Both experimental studies and theoretical models explain how several parameters affect fiber morphology (fiber diameter, surface roughness, porosity) and fiber physical properties (stiffness, toughness, electrical conductivity, thermal properties and biocompatibility and degradation properties for biomedical applications) [2, 28].

Each method has some disadvantages: drawing is a discontinuous method; phase separation is limited to several polymers; and controlling of nanofiber dimensions is not possible for drawing, phase separation and self-assembly methods while electrospinning method enables control of nanofiber dimensions and is capable of producing nanofibers at several meters length as well as nanofibrous mats [1].

Fiber lengths might be in microns for template synthesis and self-assembly methods; fibers produced by drawing method can have lengths from 10 microns to millimeters, while phase separation yields either porous structures or continuous networks [1, 24]. Electrospinning requires usage of appropriate solvent, removal of evaporating solvent, an adequate power supply to overcome the viscosity and surface tension of the polymer solution; however, jet instability and jet control remain as challenges in electrospinning [1, 3, 4].

4. FUNCTIONALIZATION OF NANOFIBERS

Nanofibers have higher surface area per weight ratios compared to microfibers and fibers [25]. The large surface area of nanofibers gives opportunity to functionalize them [29]. Nanofibers can be functionalized either by adding the functionalization material to the melt/solution during production or by surface modification by post-spinning functionalization [29, 30]. Nanofibers produced by adding the functionalizing material (such as TiO_2 ,ZnO,MgO) inside the spinning melt or solution have the material particles within the nanofiber while the surface modified nanofibers obtained by post-spinning functionalization have the material particles only on the nanofiber surface [31]. Adding the functionalization material to the melt/solution might cause increase in nanofiber thickness and decrease in mechanical properties due to agglomeration of the functionalization material particles [32].

5. CONCLUSIONS

Nanofibers have several usages including filtration and medical applications. Nanofibers exhibit superior properties compared to conventional micron scaled fiber. There are several methods to produce nanofibers. Fiber length is limited in most of the production methods, while electrospinning gives opportunity to produce long nanofibers.

Electrospinning requires usage of appropriate solvent, removal of evaporating solvent; while, jet instability and jet control remain as challenges in electrospinning [1, 3, 4]. In electrospinning, a high electric field, which is in tens of kilovolts, is applied to produce nanofibers; this high electric voltage requires attention during production [6].

Nanofiber production methods possess some disadvantages as: higher cost compared to conventional fiber production methods, health hazards such as inhale risk of nanofibers during production and keeping the environment safe from evaporating solvents used [1, 25]. Up to date, many researches have been conducted on nanofibers and electrospinning; still, more controllable, more cost effective, more environmentally friendly and safer methods are of essential importance to future applications of nanofibers.

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