

A Review of Applications of Nanofibers Fabrication via Electrospinning and Non-Electrospinning Techniques

Roaa R. Ahmed^{1*}, Ahmed J.M.AL-Zuhairi¹, Ahmad S. Lateef², Mohammed K. Khalaf³, Amer D. Majeede¹

¹Department of Physics, Physiology and Medical Physics, College of Medicine, University of Diyala, Diyala, 32001, Iraq

²Department of Physics, College of Science, Mustansiriyah University, Baghdad, 32001, Iraq

³Scientific Research Commission, Baghdad, 32001, Iraq

*Corresponding author: ruaa.r@uodiyala.edu.iq

Abstract

Nanofibers possess distinct traits and adaptable possible uses that can help with both creative approaches and chances for sustainable production of energy as well as providing innovative solutions to the complicated problems of the biomedical, medicinal, and environmental surrounded. It describes the development and Timelines of nanofiber technologies with different physical and chemical properties. It also discusses the different methods of production, including traditional methods of spinning and other non-electrospinning methods, like needleless spinning. Specifically, advanced nanofibers are employed as electrodes and membranes in solar cells, batteries, fuel cells, and supercapacitors. They are also utilized in low pressure procedures for the treatment and purification of blood, water, and wastewater, as well as membrane technologies for ultra-high efficiency air filtration systems.

Keywords

Dimensional of Nanofiber, Nanofiber History, Electrospinning, Fabrication Techniques

Received: 14 December 2025, Accepted: 15 February 2026

<https://doi.org/10.26554/ijmr.20264176>

1. INTRODUCTION

Nanofibers, a kind of one-dimensional (1D) nanomaterials, are rapidly becoming a hot topic in various fields and commercial applications (Gugulothu et al., 2018). Fibers can be up to 1,000 times smaller in diameter than a human hair, with a lot of interaction particles on surface with tunable porosity, 3D surface topographies, various surface functionalities, and stiffness and tensile strength than most bulk base materials (Huang et al., 2003). The influence of nanofibers in technology is mainly because of the extensive range of raw materials such as natural/polymers mad by chemicals materials, metals, metal oxides, carbon based materials, composite nanomaterials, etc. The bulk and surface properties of nanofibers can be engineered to incorporate a plethora of functionalities, making the range of possible applications virtually limitless (Yoo et al., 2009; Li et al., 2005). Defining nanomaterials is difficult because there is no universally accepted categorization. Nanomaterials can be labeled as nanofibers, nanoparticles, nanorods, nanowires, nanorods, and nanotubes. A nanomaterial is defined by the British Standards Institution as a substance that has a length, width, or height, and/or any other internal or surface structures at the nanoscale, which is reported as being about 100 nanometers. Nanoparticles have all three dimensions at the nanoscale, while

the other structures, such as nanofibers, are even more complex. Nanofibers have two dimensions that are at the nanoscale, and one dimension that is much larger (the Axis Z length) (Teo and Ramakrishna, 2006). Numerous examples of nanofibers (Teo and Ramakrishna, 2006) exist and can be grouped into different categories that encompass such aspects as their composition (organic, inorganic, carbon, or composite nanofibers); structure (solid, porous, non-porous, hollow, and core-shell); and even their origin (natural or engineered, as seen in Figure 1), as well as rigidity (flexible mixed with stiff) (Su et al., 2014).

Polymer nanofibers are commonly made by different methods such as drawing, template synthesis, phase separation, self-assembly, and electrospinning. However, there are many disadvantages to these technics. The majority of approaches must deal with the same negative issues. Only discontinuous nanofibers can be made using the drawing method (Ondarcuhu and Joachim, 1998). Template synthesis can only make fibers of the same diameter (Maiyalagan et al., 2006). Phase separation only works with certain, specific polymers (Ismail and Barhoum, 2025). Lastly, self-assembly techniques are known for being extremely slow (Liu et al., 1999). All these disadvantages seem to have one solution. The electrospinning method has a consistent record of creating continuous nanofibers, and has the added ability to control fiber dimensions (Hekmati et al., 2013). This method has the

added advantage of being able to produce different types of fiber arrangements. We can use electrospinning methods to produce Nonwoven fiber meshes, aligned fiber meshes, patterned fiber meshes, random three-dimensional structures, baffled springs, and even convoluted fibers (Teo and Ramakrishna, 2006). Additionally, this method has the flexibility to use many different kinds of materials including both types of polymers, liquid crystals, solid particle suspensions, ceramics, and emulsions, to produce a variety of fibers ranging between 2 nanometers and several micrometers in diameter (Pakravan et al., 2011). There are many different methods to produce nanofibers, such as top-down and bottom-up. In first way (top-down approaches), bulk materials are degraded to nanofiber scale, for example, wood pulp chemical and mechanical treatment. These methods are often used to produce cellulose nanofibers (Nayak et al., 2012). On the opposite side of the spectrum, bottom-up techniques nanofibers use constituent molecules and are used in methods such as electrospinning (Lee et al., 2018), drawing (Lee et al., 2016b), template synthesis, self-assembly, and phase separation. Of those, due to its high operational ease, low-cost apparatus, mass production capability, and ability to customize nanofiber properties (composition, diameter, and orientation) to meet end-use application needs, electrospinning remains the most popular technique (Lee et al., 2016a).

2. HISTORICAL OVERVIEW OF NANOFIBERS AND ELECTROSPINNING

As far back as 1600, Gilbert was the first to study electrostatic attraction, laying the groundwork for the electrospinning process and nanofiber history (Tucker et al., 2012; Gilbert and Wright, 1967). Other pioneers include Schwabe (Kauffman, 1993), the first to manufacture synthetic fibers, Hughes and Chambers (Hughes and Chambers, 1889), the first to make carbon filaments, and in 1902, Cooley was the first to patent an electrospinning device (Cooley, 1902). Zeleny and others' work energized the nascent science of fluids and electricity (Arinstein and Zussman, 2011). In the middle of the 20th century, Formhals patented some important methods of experimental production (Anton, 1934), and Petryanov-Sokolov became the first to use these fibers to create filtration materials (Tucker et al., 2012). Further progress was made with the first production of hollow carbon fibers (Radushkevich and Lukyanovich, 1952) and the first developed Chemical Vapor Deposition methods (Oberlin et al., 1976). In the period 1964-1969, Taylor formulated the first theories of electrospinning (Taylor, 1964; Simons, 1966; Taylor, 1969; Melcher and Taylor, 1969). Other contributors include Rayleigh (1879) and Boys (1887) who made the other principal theories on fluids and spinning technologies. Doshi and Reneker (1995) first used the term "electrospinning" in 1995, and in so doing, became the first to use the term in modern times. This event marked the commencement of exponential growth within the field, which was further distinguished by the development of inorganic fibers by Wang (Wang et al., 2001) and the publication of the first comprehensive book on the subject by Ramakrishna and colleagues (Ramakrishna et al., 2005).

3. NANOFIBER FABRICATION TECHNIQUES

3.1 Electrospinning Setup

Three fundamental components make up any standard electrospinning device: a power source, a capillary tube, a needle, and a collector screen (Jaeger et al., 1996). An example of the configuration of an electrospinning apparatus is shown in Figure (2). To begin the electrospinning process, Taylor found that about 6,000 volts needs to be applied (Taylor, 1964). However, it is possible to lower the required applied voltage to begin the process of electrospinning if a grounded target is placed closer to the spinneret (Lai et al., 2010). The electrospinning procedure has been utilized as a promising method for continuous fiber fabrication for approximately eighty years. By changing critical parameters-such as solution concentration, molecular weight, viscosity, surface tension, applied voltage, flow rate, and the distance between the syringe and the collector-electrospun nanofibers can be employed in a many applications. Various spinneret designs and constructions, such as, clip spinnerets, co-axial spinnerets, heating spinnerets, and tube-less spinnerets, are available in the industry. Each has its own unique features and benefits. For example, clip spinnerets can be cleaned easier than other spinnerets making changeover time faster (Mechanics Electronics Computer Corporation, 2014a). On the other hand, tube-less spinnerets aim to reduce the amount of solution lost in the process (Mechanics Electronics Computer Corporation, 2014b). We can applied co-axial electrospinning method at low spinnability (Mechanics Electronics Computer Corporation, 2014c). Multi-jet spinnerets facilitate the electrospinning of materials at lower voltages (Mechanics Electronics Computer Corporation, 2014a). Lastly, heating spinnerets are used to electrospin materials that require high temperatures in order to dissolve in the solution (Mechanics Electronics Computer Corporation, 2014b). Plate collector (Pedicini and Farris, 2003), rotary drum collector, grid type collector (Zhang et al., 2009), edge type collector (Theron et al., 2001), mandrel collector (Teo and Ramakrishna, 2006), steel sheet collector (Zucchelli et al., 2009), dual rings collector (Dalton et al., 2005). The researchers use these tools according based on the applications and characteristics of fiber produced. And a syringe pump with feeding rate from 0.1 to 60 mL/h is required for electrospinning process (Jalili et al., 2005).

3.2 Alternative Spinning Approaches

Methods that do not use electrospinning techniques, also called needleless spinning techniques, allow for the creation of nanofibers from much higher precursor concentrations as compared to conventional methods. In addition to these benefits, less solvent is used, and the overall production costs as well as the time it takes to manufacture nanofibers are decreased. Currently, three of the most common methods of nanofiber fabrication that do not use electrospinning include: blowing bubble spinning, centrifugal spinning, and fiber drawing. In the Bubbfil spinning process, polymer liquid, or use temperature to polymer melts, are used alongside the use of blowing air, mechanical, or electrostatic forces to overcome surface tension and create discontinuous or even smooth nanofibers. The main types of variations of Bubbfil

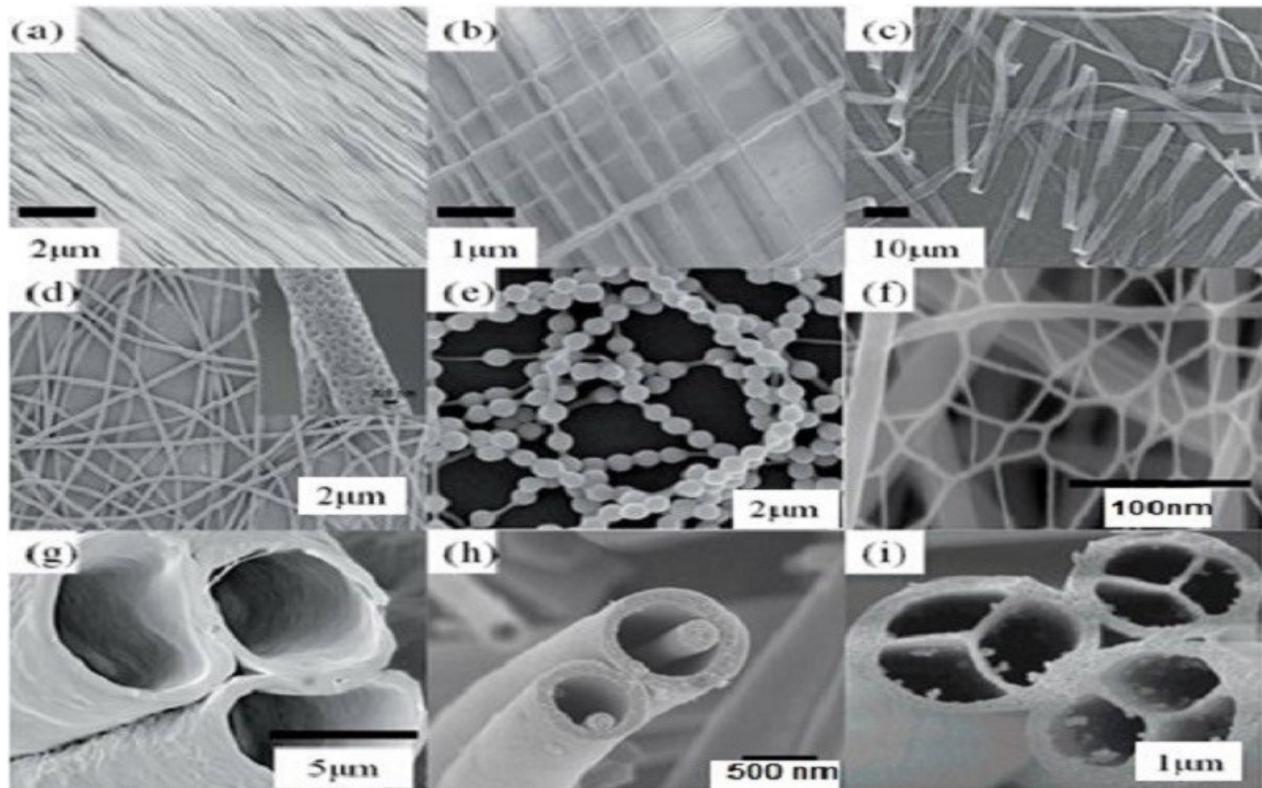


Figure 1. Shows Various Nanofiber Morphologies: (a) Uniaxially Aligned, (b) Biaxially Orientated, (c) Ribbon, (d) Porous Fibers, (e) Necklace-Like, (f) Nanoweb, (g) Hollow, (h) Nanowire-in Microtube, and (i) Multichannel Tubular (Su et al., 2014)

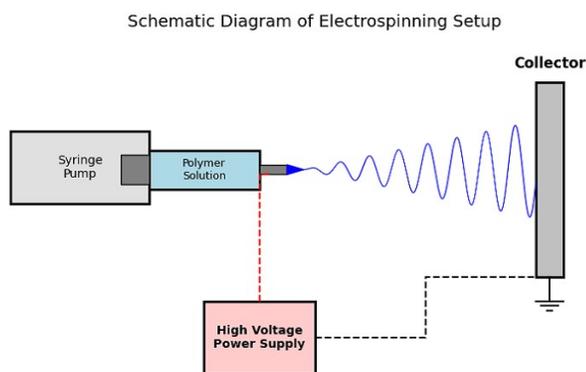


Figure 2. Schematic Diagram of Set Up of Electrospinning Apparatus

spinning are membrane spinning, bubble-electrospinning, and blown bubble spinning. In comparison to traditional electrospinning, the rate of production of fibers is much higher when bubble spinning is used, Bubbfil spinning, for example, has been reported to produce fibers at rates much higher when compared to traditional electrospinning (Medeiros et al., 2009). The blown bubble spinning method uses a gas, such as nitrogen or air, to

drive the creation of fibers through a concentric nozzle while simultaneously encouraging solvent evaporation. In this instance, the height gas pressure, solution injection rate, and different between nozzle-to-collector distance, and diameter of nozzle and shape are the most crucial processing characteristics. Additionally, by using a low-voltage electric field to push fiber on the collector, bubble electrospinning and air-jet aided bubble electrospinning have been produced Figure (3) (Chen et al., 2014). This technique is particularly implemented for the electro-spinning of high molecular weight polymers, which are difficult to be fabricated with conventional electrospinning configurations because its Taylor cone formation requires a higher surface tension. Lastly, the method of melt blowing is another gas method to assisted spinning method sometimes is applied to materials when has low dielectric constant or electrical conductivity (Medeiros et al., 2009; Chen et al., 2014).

Fibril strands are the main product of flash-spinning. It works especially well for processing polymers that are hard to dissolve, like high molecular weight polymers and polyolefins. Plexi-filamentary film-fibril strands are typically produced by decompressing a saturated solution is high of a polymer and low temperature and pressure spin agent (solvent) via a spin orifice. The polymer then splits into a fibril as the spin agent (solvent) evaporates. The spin agent must have certain properties in order for this process to be successful: (i) it must act as a non-solvent

to the polymer less its normal boiling point; (ii) dispersion it must do a two-phase with the polymer at low pressure; (iii) at increase in the solution pressure it must form a solution with the polymer upon an; and (iv) at a low-pressure zone it must vaporize when the flash is released into (Nayak et al., 2012). Several additional non-electrospinning methods have also been documented in the literature. Such as, laser spinning allows the creation of tailored chemical compositions of ultra-long nanofibers (Quintero et al., 2007, 2009). In this technique, a high-powered laser evaporates a small volume of precursor materials. A amorphous nanofibers which produces after a supersonic gas jet is injected where causes further elongation of the molten precursor (Sutti et al., 2011; Penide et al., 2014). Precipitation occurs when a polymer is drawn through a spinneret and into a non-solvent during wet spinning (Yokoyama et al., 2009). The spinneret itself introduces the spinning solution into the non-solvent, causing precipitation or coagulation. This is particularly advantageous for spinning highly viscous materials that cannot be processed using other spinning methods (Meier and Welland, 2011). In the islands-in-the-sea technique, melt spinning of two different polymer components, the 'sea' and 'island' is performed at spinning speeds of 400 to 6,000 meters per minute. A bundle of thin fibers with a diameter of 10 to 1,000 nanometers is created after the "sea" polymer in the composite fiber is dissolved and removed. High spinneret density and flexible polymer selection are two appealing benefits of this method. The diameter and form of the spinneret hole, along with the distribution of polymers in the distribution plates, calculate the number of islands produced and the cross-sectional area (Kamiyama and Numata, 2009).

4. EFFECT OF ELECTROSPINNING PARAMETERS

4.1 Effect of Voltage

In general, initiating the jet formation requires an applied voltage of more than 6 kilovolts (Taylor, 1964). At this and even higher voltage levels, the polymer solution may be ejected at an even greater rate (Demir et al., 2002). In addition, more charged solutions tend to have greater electrostatic, and, hence, stretching, as well as greater repulsive, stretching, and slowing forces on the fluid jets. This, in turn, causes greater formation smaller diameter fibers (Buchko et al., 1999). The applied voltage also effects the molecular structure of the fibers. Mostly at higher levels, the polymer molecules become more ordered as a result of the electrostatic forces, and this, in turn, enhances the fiber's crystallinity. Yet, beyond a certain voltage level, this situation may also be reversed, as the jets have less molecular alignment, due to decreased flight times (Zhao et al., 2004).

4.2 Effect of Flow Rate

The electrospinning solution's flow rate has a substantial impact on the diameter, porosity, and geometry of its electrospun nanofibers. To achieve uniform and bead-free fiber production, the polymer solution must have sufficient time for polarization. Therefore, a steady but slow flow rate is advisable (Yuan et al., 2004). However, a minimum flow rate is essential for the electrospinning process to work (Zeleny, 1935). In most cases, a greater

flow rate is associated with greater pore size and fiber diameter. However, If the rate of flow is too high, the tendency for bead formation is significantly increased (Taylor, 1969).

4.3 The Impact of Different Types of Collector

In conventional electrospinning set-ups, a conducting target disk is commonly used to create the required electric potential difference between the emitting and collecting elements. Based on the characteristics of fibers for different applications, a wide range of collector geometries such as pin types, wire meshes, plates with protrusion arrays, series of parallel ridges, grids, parallel bars rotating wheels and liquid non solvent bath have been used by researchers (Ki et al., 2007). On the other hand in the case where collector is made of a non-conductive or low conductive material the current jets are deposited (and even remain) on collector surface very quickly. As the result, deposited fibres amount is much decreased and the risk of producing beaded fibers is increased (Wang et al., 2005).

4.4 Impact of the Distance Between the Collector and the Needle Tip

Fibre properties can radically change by adjusting the Impact of the distance between the collector and the needle tip. In comparison with more predominant factors affecting the electrospinning process, these effects may not be as easily identifiable (Zhang et al., 2005; Geng et al., 2005). Defect fibres can be created if the Impact of the distance between the collector and the needle tip is insufficient. Charge jets have a shorter distance to travel to the collector which means more time will be needed for the solvent to evaporate and the fibre to solidify. This can lead to intra- and inter-layer bonding at fibre junctions to create beaded fibres On the other hand, greater distance from the collector to the emitter does seem to lead less average fibre diameters (Doshi and Reneker, 1995). However, this is not universal; for example, with fewer electrostatic forces over greater distance, Lee and colleagues were able to create polyvinyl alcohol fibres with larger diameters (Lee et al., 2004). Finding an optimum distance between the collector and the needle is clearly essential to create processes to ensure electrospinning is bead-free (Ki et al., 2005).

5. CHARACTERIZATION OF ELECTROSPUN NANO-FIBERS

5.1 Physical Characterization

Determining all of a material's unique physical characteristics, example stability, melting point, and water uptake, all that is typically included in physical characterization. Thermal characteristics can be measured with a differential scanning calorimeter. like the glass transition temperature, melting point, and crystallization point. A thermogravimetric analyzer is frequently used to assess the thermal stability of a substance by measuring the mass loss that takes place in a regulated heating ramp. Furthermore, the air and vapor transport characteristics of nanofibrous mats are assessed using a dynamic moisture vapor permeation cell (Gibson et al., 1995). Additionally, investigating the optical

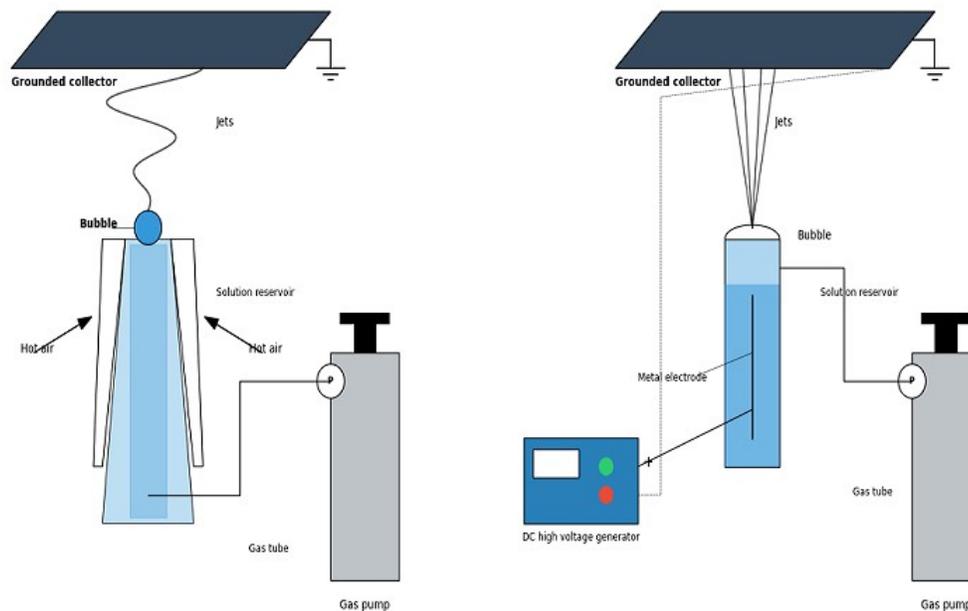


Figure 3. Shows a Schematic Illustration of the Air-Assisted Fiber-Spinning System Utilized for: (A) Blown Bubble Spinning, where the Only Active Force is Blowing Air; and (B) Bubble Electrospinning, which Allows for Adjustable Bubble Size

properties, such as the optical constants of polymer blends, is crucial for applications requiring light interaction (Rouaramadan and Hasan, 2013).

5.2 Geometrical Characterization

The process of geometrical characterization entails a thorough examination of the geometric characteristics of nanofibers, including their diameter, diameter distribution, orientation, and general morphology. These geometric properties are characterized using advanced imaging techniques like AFM, TEM, FE-SEM, and SEM (Schreuder-Gibson et al., 2002). Notably, scanning electron microscopy has been utilized by numerous researchers to examine fiber shape in great detail (Fong and Reneker, 1999).

5.3 Chemical Characterization

A material's chemical characterization yields crucial information about its elemental and molecular makeup. Nuclear magnetic resonance techniques and Fourier transform infrared spectroscopy can be used to accurately determine the chemical composition of electrospun fibers (Huang et al., 2000). Furthermore, X-ray photoelectron spectroscopy, attenuated total reflection Fourier transform infrared spectroscopy, and water contact angle study of the nanofiber membrane surface can be utilized to evaluate the nanofibers' surface chemical characteristics (Deitzel et al., 2002). Additionally, researchers have regularly used FTIR and IR to look into particular changes that might be taking place at the molecular level (Wang et al., 2003).

5.4 Mechanical Characterization

Nanofibrous nonwoven membranes can be characterized using standard mechanical testing methods (Matthews et al., 2002; Huang et al., 2001). This involves applying mechanical loads to, in situ, prepared specimens from electrospun ultra-fine nonwoven fiber mats. The mechanical characterization of nanofibers and nanowires has been approached from different methodologies and includes the use of micro and nanoindentation, bending and resonance frequency tests, and microscale tension test (Lee et al., 2002). Furthermore, Young's modulus, tensile strength, and strain at break can be determined by tensile testing individual polymer fibers. The Nano Bionix System (MTS, Tennessee, USA) is a commercial nano-tensile testing system used for tensile testing of single polymeric ultrafine fibers of polycaprolactone, according to Tan et al.'s paper on tensile testing. Some investigators have applied resonant contact atomic force microscopy for the determination of the nanofiber's elastic modulus (Cuenot et al., 2003). The nanofiber must be securely connected to the cantilever tip in order to use this testing procedure (Yuya et al., 2007).

6. APPLICATION OF ELECTROSPUN NANOFIBERS

6.1 Reinforcing and Self-Healing Materials

Polymeric substances often fail to cater to the complete set of standards necessary to meet the requirements of some of the commercial applications. Polymeric nanocomposites/nanofibers, when compared to macrocomposites, offer more advantages with the same amount of nanofillers, attaining an equally high me-

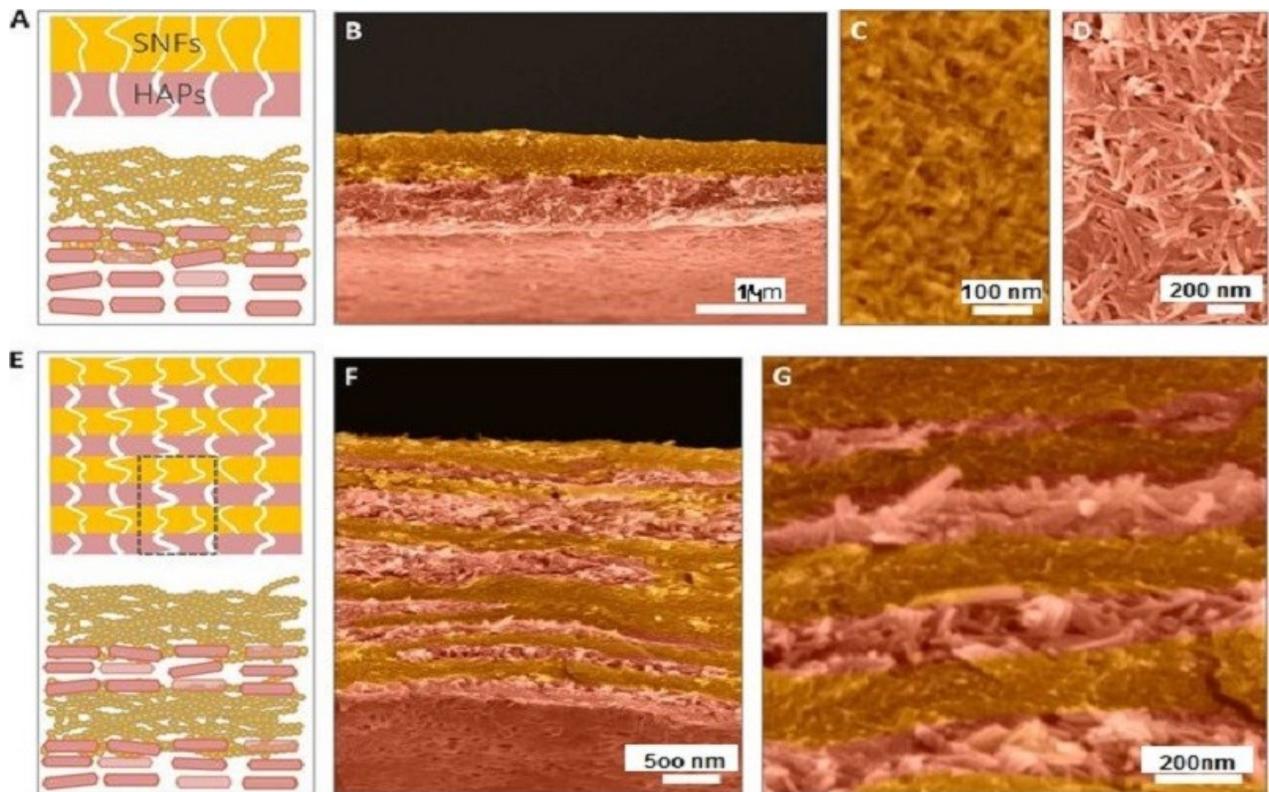


Figure 4. Self-Assembled Multilayer Membrane for Water Treatment Using Silk Nanofiber (SNF) and Hydroxyapatite (HAP). (A) Double-Layer Structure with Larger-Sized Pores in the Bottom HAP Layer and Smaller-Sized Pores in the Top SNF-Rich Layer. (B) SEM Picture in Cross-Section. (C) SNF-Rich Layer SEM Image (Top View). (D) HAP-Rich Layer SEM Image (Top View). From E to G the SNF/HAP Membrane's Multilayer Structure Is Shown in (E) a Schematic Representation and (F,G) Cross-Sectional SEM Images (Ling et al., 2017)

chanical strength (Lee et al., 2015). This performance may be due to the controlled dimensions, morphology, and dispersion of the nanofillers. Fibers, especially nanofibers, have a greater interfacial adhesion because of the increased surface area to volume ratio compared to ordinary fibers (Lee et al., 2018). Though there is a copious amount of reinforcing research on carbon nanofibers, incorporating them into a polymer matrix causes an undesirable increase in matrix viscosity (Lee et al., 2016b). To overcome such challenges, novel techniques have been used wherein carbon nanofiber sheets (produced by filtering well-dispersed carbon nanofibers under controlled conditions) are used in conjunction with the autoclave method to fabricate composite laminates.

6.2 Electrospun Nanofibers in Filtration Purposes

The process of filtration is important for both domestic and industrial operations, and it involves the separation of solid particulates from the air and liquid phases. Because of the high porosity and enormous surface area to volume ratios of its microstructure, and many interconnections. Outstanding filtration attributes are held by nanofibers. Recently, manufacturers of air filtration systems have started to utilize nanofiber mats in their products. Since nanofibers are around 800 times smaller than traditional filtration media, nanofiber mats provide better filtration than

the other mats. In the study conducted by Arumuganathan et al. (2007) on the filtration performance of nanofiber media in vehicle cabins, it was found that the nanofiber composite filters outperformed the standard cellulose filters, for which the removal efficiencies were 68 and 86%, with a removal efficiency of 92% for submicron and respirable dust (greater than 1 micrometer) particles. Among the many existing membrane technologies for the rigorous removal of micrometer-sized suspended solids in the context of water purification, microfiltration and ultrafiltration are the most common. They are also commonly made through the phase inversion method (Amri et al., 2025). Arumuganathan et al. (2007) evaluated how well nanofiber media reduced pollutant concentrations in automobile cabins. The results showed that standard cellulose filters had removal rates of 68% and 86%, respectively, while nanofiber composite filters had a removal efficiency of 92% for both sub-micron and respirable dust particles (exceeding 1 micrometer). Membrane technologies like microfiltration and ultrafiltration are widely used in water purification to remove micron-sized suspended solids. Usually, the phase inversion method (Jeong et al., 2007), electrospinning, melt-blown, and spun-bonding techniques (Barnes et al., 2007) are used to create these membranes. In addition, nanofiber membranes can

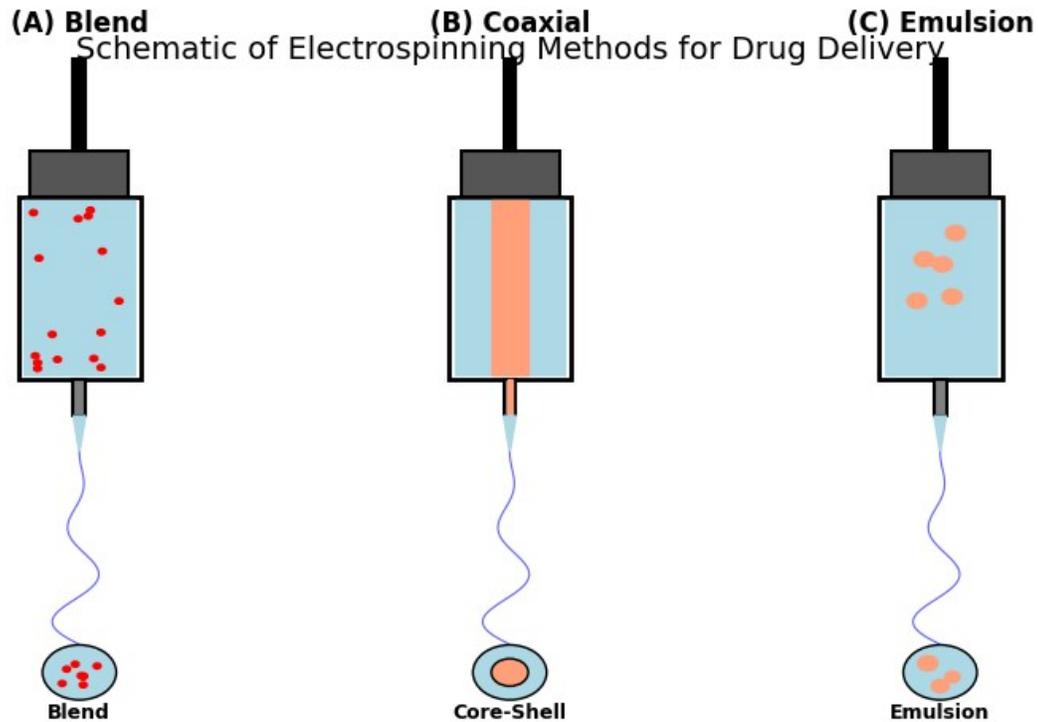


Figure 5. Diagrammatic Representation of Different Methods for Creating Drug-Loaded Nanofibers: (I) A Schematic Representation of Emulsion, Coaxial, and Mix Electrospinning; (II) The Cooperative Use of Nanofibers and Nanocontainers; (III) Electrospun Nanofiber Surface Functionalization

remove submicron particulates such as bacteria and dust by size exclusion. However, for the removal of nanoparticles such as viruses, much smaller pore sizes are required which severely reduces the water flux. To address this trade-off, multi-level nanofiber membranes are being developed which can provide high filtration efficiency and good water permeation. However, this potential is yet to be fulfilled as it is technically difficult to prepare membranes with a precisely controlled and multilayered structure with dimensions in the nano scale. Addressing this, Ling and associates recently developed biomimetic multilayer nanofiber membranes tailored for the efficient extraction and recovery of diverse contaminants, including heavy metal ions, dyes, and proteins from aqueous solutions (Ling et al., 2017).

7. NANOFIBERS FOR BIOMEDICAL APPLICATIONS

There is growing recognition of the application of nanofibers in drug delivery systems, tissue engineering, burn and wound care, blood purification, and illness therapy. The enormous surface area of nanofibers facilitates the construction of lightweight devices with significant cost savings while also improving cell, protein, and medicinal drug adherence (Gugulothu et al., 2018). The most common biomedical uses of nanofibers will be outlined in the section that follows, along with an analysis of the critical factors influencing their effectiveness.

7.1 Electrospun Nanofibers in Wound Dressing

Compared to traditional skin substitutes made by freeze-drying, which are usually structurally heterogeneous, scaffolds created by the electrospinning process are more homogeneous. Powell et al. (2008) evaluated the distribution, proliferation, cellular structure, and healing of full-thickness wounds in thymic mice using freeze-dried and electrospun collagen scaffolds. The use of electrospun scaffolds significantly decreased wound contraction, but the results showed no significant difference in the previously mentioned parameters. As a result, the morbidity related to electrospun collagen skin substitutes decreased. Similar to the natural extracellular matrix, these scaffolds are essential for the development of new, healthy tissue in an injured location, which lessens the formation of scars (Huang et al., 2003).

7.2 Membranes for Blood Filtration

For individuals with kidney failure, hemodialysis is an essential therapeutic option that can be carried out at a hospital or at home. Nevertheless, the conventional machines utilized for blood filtration essentially replacing renal function—are frequently characterized by their substantial size, high cost, and requirement for intensive maintenance. A wearable nanofiber mesh that could be more affordable than conventional hemodialysis equipment was recently created by researchers (Namekawa et al., 2014). Specifically, the blood-contacting membrane within this device

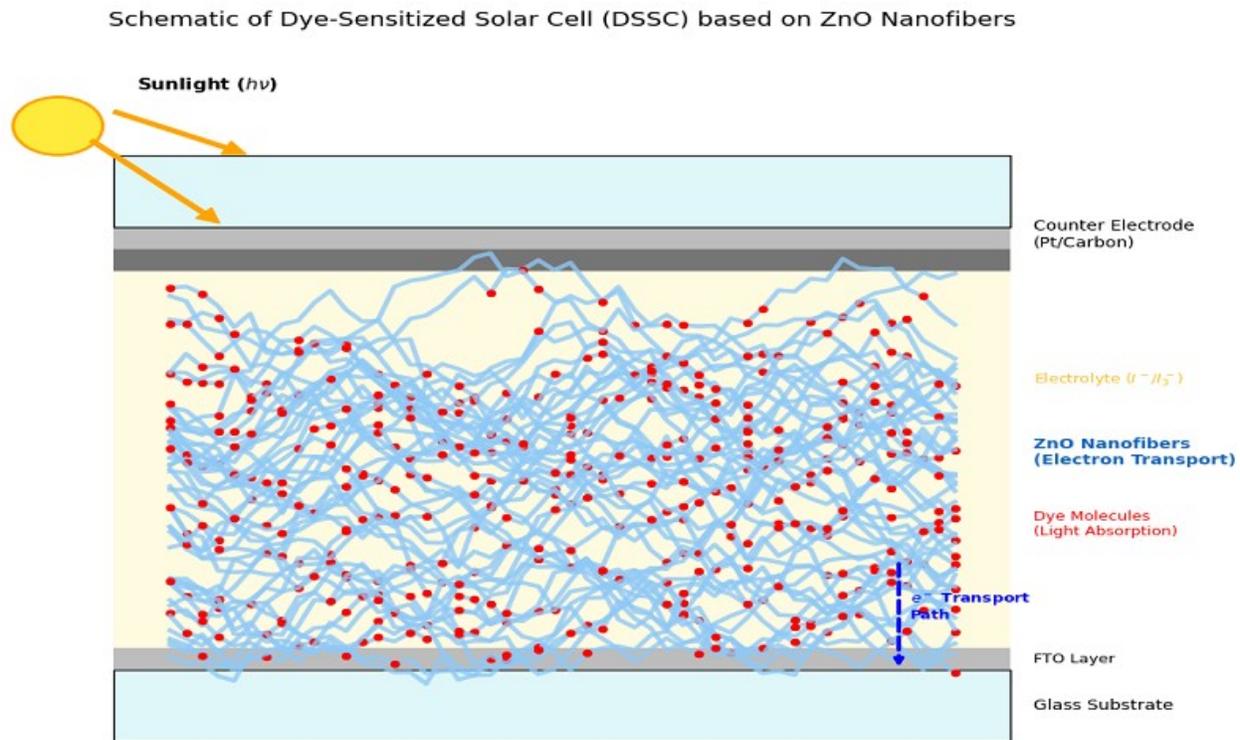


Figure 6. Schematic of Dye-Sensitized Solar Cell (DSSC) Based on ZnO Nanofibers

is fabricated from an electrospun polyethylene-co-vinyl alcohol polymer.

7.3 Muscles

In the past, collagen nanofibers were used to grow smooth muscle cells. Cell growth, in this instance, was very positive, as the cells were successfully integrated within the nanofiber network seven days post-seeding. Furthermore, smooth muscle cells attached to and multiplied in the presence of additional polymer nanofiber mats that had been mixed with collagen. Collagen was added to promote cell adhesion, fiber strength and pliability, and cellular proliferation (Stankus et al., 2004). In terms of cell attachment, the wettability of fibers and the alignment of nanofibers are the most important parameters. For example, Baker and his team noted that cell attachment was enhanced by 100% when increase wettability was created by treating polystyrene nanofibers with argon plasma (Baker et al., 2006). Furthermore, aligned nanofibers have been shown to promote cell orientation, the growth of aligned myotubes, and other important biological phenomena such as the morphogenesis of skeletal muscle cells.

7.4 Drug Delivery

Researchers have investigated the delivery of large macromolecules (proteins and nucleic acids, such as DNA and RNA) and tiny chemical medicines using nanofibers. However, in order to start evaluating the safety and toxicity of these systems, some

kind of in vivo pre-clinical testing must come before clinical testing and marketing approval (Uludağ, 2014). The bulk phase of electrospun nanofibers can incorporate bioactive molecules, and the surfaces of nanofibers can be coated using a variety of techniques, including coaxial and emulsion electrospinning, Co-electrospinning of drug-polymer complexes and immobilization of drug-loaded nanocarriers on nanofibers, and nanofiber post-treatment at Figure (5). This method is the most common, and for good reason; it requires no post-fabrication processing (simplifying the whole process) and it is usually less expensive. Initial studies primarily focused on the development of slow-release drug delivery systems from electrospun nanofibers by capturing various antibacterial and anti-tumor agents (Yu et al., 2018). These therapeutic agents can be entrapped by either blending them with the polymers and electrospinning them as one to form the fibers, or by fabricating them as part of a core-shell structure with the use of a coaxial spinneret (Yang et al., 2009). Additionally, drug release can be regulated to treat conditions like AIDS and various cancer types by changing electrospinning parameters including fiber diameter and mesh size (Okuda et al., 2010).

8. ELECTROSPUN NANOFIBERS IN RENEWABLE ENERGY

The demand for energy has increased beyond reasonable bounds in the age of contemporary civilization. As a result, current cutting-edge research has concentrated on creating innovative

Table 1. Summary of Key Applications, Materials, and Results of Nanofibers Discussed in This Review

Application Field	Specific Application	Material / Polymer	Key Outcomes / Results
Filtration	Air Filtration (Vehicle Cabins)	Nanofiber Composite Media	Achieved 92% removal efficiency for submicron particles, outperforming standard cellulose filters (68–86%) (Arumuganathan et al., 2007).
Filtration	Water Purification	Silk Nanofiber (SNF) & Hydroxyapatite (HAP)	Developed biomimetic multilayer membranes capable of efficient extraction of heavy metals and dyes (Ling et al., 2017).
Biomedical	Wound Dressing	Electrospun Collagen Scaffolds	Reduced wound contraction and promoted healthy tissue development compared to freeze-dried substitutes (Powell et al., 2008).
Biomedical	Blood Filtration (Hemodialysis)	Polyethylene-co-vinyl alcohol	Enabled the fabrication of compact, wearable blood filtration devices for kidney failure patients (Namekawa et al., 2014).
Biomedical	Tissue Engineering (Muscle)	Polystyrene (argon plasma treated)	Enhanced cell attachment by 100% due to increased wettability, promoting myotube growth (Baker et al., 2006).
Energy	Fuel Cells (PEM)	Sulfonated Aromatic Hydrocarbon	Exhibited superior mechanical strength and thermal stability compared to commercial Nafion membranes (Guo et al., 2009).
Energy	Solar Cells (DSSC)	TiO ₂ Nanofibers	Enhanced penetration of viscous polymer gel electrolytes, increasing conversion efficiency (Song et al., 2004).

processes for renewable energy with the dual goals of preserving regional stability and reducing the strain on fossil fuel sources. Since electrospun nanofibrous materials provide better energy conversion and storage efficiency than their bulk equivalents, nanotechnology offers new potential in this field. Electrospun nanofibers show improved performance in two main applications: fuel cells and solar cells.

8.1 Fuel Cells

In the twenty-first century, fuel cells are considered an effective renewable energy source result a chemical reaction with oxygen or another oxidizing agent, where chemical energy transform from a fuel into electrical energy (Khurmi and Sedha, 2008). One of the essential parts of a fuel cell system is the proton exchange membrane (Steele and Heinzl, 2001), and Nafion has been used extensively as a proton exchange membrane (Choi et al., 2006). Nafion's exorbitant cost, low thermal stability, and high gas permeability have made it less desirable. Because of their superior mechanical strength, chemical stability, and thermal stability, electrospun polymer electrolyte membranes made of sulfonated aromatic hydrocarbon polymers offer a promising substitute for Nafion (Guo et al., 2009). Alternatively, polymer blends of Nafion and polyethylene oxide nanofibers can exhibit high proton conductivity (Lee et al., 2009).

8.2 Solar Cells

Photovoltaic effect enables solar cells to transform light energy into electrical energy. Photoelectric cells as solar cells generate different electrical responses according to the light they are exposed to (O'Regan and Grätzel, 1991). An electrolyte was used previously in dye-sensitized solar cells. This was because the dye-anchored mesoporous nanoparticle thin layer was not working adequately as it needed a greater specific surface area and more pores to induce the light-electricity conversion process (O'Regan et al., 2000). Increasing the photocurrent in dye sensitized solar cells can be achieved by using one-dimensional electrospun nanofibers, as they can enhance the penetration of viscous polymer gel electrolytes (Song et al., 2004). In order to maintain high photo-electric conversion efficiency, organic solar cells have a protective layer that blocks light with a wavelength of less than 450 nanometers in addition to a charge-generating and charge-transporting component (Mohammed, 2024).

9. OPPORTUNITIES AND FUTURE CHALLENGES

As of today, nanofiber technology has progressed to the point of the creation of nanofibers from a wide range of sources, when it's found both natural and synthetic. Additional sources include metals, ceramics, and a variety of complex organic and inorganic composites, or inorganic composites. The manufacturing of a variety of materials into one device can provide several unique characteristics, such as the polymer's flexibility and the electrical

conduction of dopants into the metal. Because of this, there is a significant manufacturing challenge, making it increasingly difficult to gain insight into the optimal manufacturing conditions as well as the various solution phases. The presence of functional or incorporated nanofibers will provide the basis for additional possibilities and more flexible materials made from nanofibers. Each of the various fabrication processes is aimed at improving nanofiber characteristics and scaling the production processes. Among the fabrication technologies used, the ability to produce nanofibers from various materials and different fibrous structures is one of the electrospinning techniques because of the fast manufacturing rate and straightforward configuration. This favored electrospinning as the best choice for research and industrial application (Rasouli and Barhoum, 2019; Rasouli et al., 2019; Chen et al., 2018; Turkey et al., 2017; Makhoulouf and Barhoum, 2018).

10. CONCLUSIONS

This review focused on the recent progress made in the fabrication of nanofibers and the numerous ways they can be used. Although electrospinning is the most used method to manufacture continuous nanofibers, and to control the morphology, surface area, and volume ratio to that of the nanofibers, methods that do not involve electrospinning, including solution blow spinning and centrifugal spinning, are now considered the most promising for mass production. Nanofibers have unique chemical and physical properties. They demonstrated the ability to remove heavy metals and submicron particles from air and water. In the medical field, the nanofibers stimulate cell growth and regeneration by mimicking the extracellular matrix and so are used for wound dressing, and systems for delivering drugs as well as tissue engineering. In the field of renewable energy, the nanofibers improve the transport of charge and the uptake of electrolytes in the dye-sensitized solar cells DSSCs and in the fuel cells PEMFCs. The obstacles faced by the large-scale production of the described technologies have to be addressed.

11. ACKNOWLEDGEMENT

The authors are grateful to the Department of Physics, Physiology and Medical Physics / College of Medicine / University of Diyala, Diyala, Iraq.

REFERENCES

Amri, A., S. Wibiyani, and E. S. Fitri (2025). Selectivity of Ni/Al LDH Material Supported by Green Tea Leaf (*Camellia sinensis*) Extract as an Adsorbent for Removing Cationic Dyes in Wastewater Treatment. *Indonesian Journal of Material Research*, 3(1); 13–16

Anton, F. (1934). Process and Apparatus for Preparing Artificial Threads

Arinstein, A. and E. Zussman (2011). Electrospun Polymer Nanofibers: Mechanical and Thermodynamic Perspectives. *Journal of Polymer Science Part B: Polymer Physics*, 49(10); 691–707

Arumuganathan, S., S. N. Jayasinghe, and N. Suter (2007). Versatile Methodology for Generating Size-Controlled Composite Micrometer Beads Capsulating Nanomaterials. *Micro and Nano Letters*, 2; 30–34

Baker, S. C., N. Atkin, P. A. Gunning, N. Granville, K. Wilson, D. Wilson, and J. Southgate (2006). Characterisation of Electrospun Polystyrene Scaffolds for Three-Dimensional In Vitro Biological Studies. *Biomaterials*, 27(16); 3136–3146

Barnes, C. P., C. W. Pemble, D. D. Brand, D. G. Simpson, and G. L. Bowlin (2007). Cross-Linking Electrospun Type II Collagen Tissue Engineering Scaffolds with Carbodiimide in Ethanol. *Tissue Engineering*, 13(7); 1593–1605

Boys, C. V. (1887). On the Production, Properties, and Some Suggested Uses of the Finest Threads. *Proceedings of the Physical Society of London*, 9(1); 8–19

Buchko, C. J., L.-C. Chen, Y. Shen, and D. C. Martin (1999). Processing and Microstructural Characterization of Porous Biocompatible Protein Polymer Thin Films. *Polymer*, 40(26); 7397–7407

Chen, R.-X., Y. Li, and J.-H. He (2014). Mini-Review on Bubble Spinning Process for Mass-Production of Nanofibers. *Matéria (Rio de Janeiro)*, 19(4); 325–343

Chen, X., L. Cheng, H. Li, A. Barhoum, Y. Zhang, X. He, W. Yang, M. M. Bubakir, and H. Chen (2018). Magnetic Nanofibers: Unique Properties, Fabrication Techniques, and Emerging Applications. *ChemistrySelect*, 3(31); 9127–9143

Choi, P., N. H. Jalani, T. M. Thampan, and R. Datta (2006). Consideration of Thermodynamic, Transport, and Mechanical Properties in the Design of Polymer Electrolyte Membranes for Higher Temperature Fuel Cell Operation. *Journal of Polymer Science Part B: Polymer Physics*, 44(16); 2183–2200

Cooley, J. F. (1902). Apparatus for Electrically Dispersing Fluids

Cuenot, S., C. Frétigny, S. Demoustier-Champagne, and B. Nysten (2003). Measurement of Elastic Modulus of Nanotubes by Resonant Contact Atomic Force Microscopy. *Journal of Applied Physics*, 93(9); 5650–5655

Dalton, P. D., D. Klee, and M. Müller (2005). Electrospinning with Dual Collection Rings. *Polymer*, 46(3); 611–614

Deitzel, J. M., W. Kosik, S. McKnight, N. Beck Tan, J. M. DeSimone, and S. Crette (2002). Electrospinning of Polymer Nanofibers with Specific Surface Chemistry. *Polymer*, 43(3); 1025–1029

Demir, M. M., I. Yilgor, E. A. Yilgor, and B. Erman (2002). Electrospinning of Polyurethane Fibers. *Polymer*, 43(11); 3303–3309

Doshi, J. and D. H. Reneker (1995). Electrospinning Process and Applications of Electrospun Fibers. *Journal of Electrostatics*, 35(2); 151–160

Fong, H. and D. H. Reneker (1999). Elastomeric Nanofibers of Styrene-Butadiene-Styrene Triblock Copolymer. *Journal of Polymer Science Part B: Polymer Physics*, 37(24); 3488–3493

Geng, X., O.-H. Kwon, and J. Jang (2005). Electrospinning of Chitosan Dissolved in Concentrated Acetic Acid Solution. *Biomaterials*, 26(27); 5427–5432

Gibson, P., C. Kendrick, D. Rivin, L. Sicuranza, and M. Charmchi (1995). An Automated Water Vapor Diffusion Test Method for Fabrics, Laminates, and Films. *Journal of Industrial Textiles*,

- 24(4); 322–345
- Gilbert, W. and E. Wright (1967). *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure: Physiologia Nova, Plurimis & Argumentis, & Experimentis Demonstrata*. Excudebat Short
- Gugulothu, D., A. Barhoum, R. Nerella, R. Ajmer, and M. Bechelany (2018). Fabrication of Nanofibers: Electrospinning and Non-Electrospinning Techniques. In A. Barhoum, M. Bechelany, and A. S. H. Makhlof, editors, *Handbook of Nanofibers*. Springer International Publishing, Cham, pages 1–34
- Guo, M., B. Liu, Z. Liu, L. Wang, and Z. Jiang (2009). Novel Acid–Base Molecule-Enhanced Blends/Copolymers for Fuel Cell Applications. *Journal of Power Sources*, **189**(2); 894–901
- Hekmati, A. H., A. Rashidi, R. Ghazisaeidi, and J.-Y. Dreon (2013). Effect of Needle Length, Electrospinning Distance, and Solution Concentration on Morphological Properties of Polyamide-6 Electrospun Nanowebs. *Textile Research Journal*, **83**(14); 1452–1466
- Huang, L., R. A. McMillan, R. P. Apkarian, B. Pourdeyhimi, V. P. Conticello, and E. L. Chaikof (2000). Generation of Synthetic Elastin-Mimetic Small Diameter Fibers and Fiber Networks. *Macromolecules*, **33**(8); 2989–2997
- Huang, L., K. Nagapudi, R. P. Apkarian, and E. L. Chaikof (2001). Engineered Collagen-PEO Nanofibers and Fabrics. *Journal of Biomaterials Science, Polymer Edition*, **12**(9); 979–993
- Huang, Z.-M., Y.-Z. Zhang, M. Kotaki, and S. Ramakrishna (2003). A Review on Polymer Nanofibers by Electrospinning and Their Applications in Nanocomposites. *Composites Science and Technology*, **63**(15); 2223–2253
- Hughes, T. and C. Chambers (1889). *Manufacture of Carbon Filaments*
- Ismail, R. K. and A. Barhoum (2025). Advances in Biosynthesis of Nanoparticles: A Review. *Indonesian Journal of Material Research*, **3**(2); 31–40
- Jaeger, R., H. Schonherr, and G. J. Vancso (1996). Chain Packing in Electrospun Poly(Ethylene Oxide) Visualized by Atomic Force Microscopy. *Macromolecules*, **29**(23); 7634–7636
- Jalili, R., S. A. Hosseini, and M. Morshed (2005). The Effects of Operating Parameters on the Morphology of Electrospun Polyacrylonitrile Nanofibers. *Iranian Polymer Journal*, **14**(12); 1074–1082
- Jeong, J. S., S. J. Park, Y. H. Shin, Y. J. Jung, P. S. Alegaonkar, and J. B. Yoo (2007). Fabrication of Carbon Nanotube Embedded Nylon Nanofiber Bundles by Electrospinning. In *Solid State Phenomena*, volume 124. pages 1125–1128
- Kamiyama, M. and M. Numata (2009). Islands-in-Sea Type Composite Fiber and Process for Producing the Same
- Kauffman, G. B. (1993). Rayon: The First Semi-Synthetic Fiber Product. *Journal of Chemical Education*, **70**(11); 887–889
- Khurmi, R. S. and R. S. Sedha (2008). *Materials Science*. S. Chand and Company, New Delhi
- Ki, C. S., D. H. Baek, K. D. Gang, K. H. Lee, I. C. Um, and Y. H. Park (2005). Characterization of Gelatin Nanofiber Prepared from Gelatin–Formic Acid Solution. *Polymer*, **46**(14); 5094–5102
- Ki, C. S., J. W. Kim, J. H. Hyun, K. H. Lee, M. Hattori, D. K. Rah, and Y. H. Park (2007). Electrospun Three-Dimensional Silk Fibroin Nanofibrous Scaffold. *Journal of Applied Polymer Science*, **106**(6); 3922–3928
- Lai, X., D. Wu, and D. Sun (2010). Electro Spinning under Sub-Critical Voltage. In *2010 5th IEEE International Conference on Nano/Micro Engineered and Molecular Systems (NEMS)*. IEEE, pages 1170–1173
- Lee, H., J. H. Kim, H. Yoon, J. H. Kim, and J. H. Park (2016a). The Chemical Deposition Method for the Decoration of Palladium Particles on Carbon Nanofibers with Rapid Conductivity Changes. *Nanomaterials*, **6**(12); 226
- Lee, H., K. H. Kim, J. S. Park, and J. H. Kim (2018). Control of the Morphology of Cellulose Acetate Nanofibers via Electrospinning. *Cellulose*, **25**(5); 2829–2837
- Lee, H., H. Yoon, J. H. Kim, J. H. Park, and J. H. Kim (2016b). Hand-spinning Enabled Highly Concentrated Carbon Nanotubes with Controlled Orientation in Nanofibers. *Scientific Reports*, **6**; 37590
- Lee, J. S., K. H. Choi, H. D. Ghim, S. S. Kim, D. H. Chun, H. J. Kim, and W. S. Lyoo (2004). Role of Molecular Weight of Atactic Poly(Vinyl Alcohol) (PVA) in the Structure and Properties of PVA Nanofabric Prepared by Electrospinning. *Journal of Applied Polymer Science*, **93**(4); 1638–1646
- Lee, K. H., H. Y. Kim, Y. M. La, D. R. Lee, and N. H. Sung (2002). Influence of a Mixing Solvent with Tetrahydrofuran and N, N-Dimethylformamide on Electrospun Poly(vinyl chloride) Nonwoven Mats. *Journal of Polymer Science Part B: Polymer Physics*, **40**(19); 2259–2268
- Lee, K. M., J. Choi, R. Wycisk, P. N. Pintauro, and P. Mather (2009). Nafion Nanofiber Membranes. *ECS Transactions*, **25**(1); 1451–1458
- Lee, M. W., H. J. Park, J. H. Park, J. Y. Kim, and S. H. Kim (2015). Self-Healing Nanofiber-Reinforced Polymer Composites. Part 1: Tensile Testing and Recovery of Mechanical Properties. *ACS Applied Materials & Interfaces*, **7**(35); 19546–19554
- Li, D., J. T. McCann, and Y. Xia (2005). Use of Electrospinning to Directly Fabricate Hollow Nanofibers with Functionalized Inner and Outer Surfaces. *Small*, **1**(1); 83–86
- Ling, S., Q. Wang, D. Zhang, Y. Zhang, X. Mu, D. L. Kaplan, and M. J. Buehler (2017). Design and Function of Biomimetic Multilayer Water Purification Membranes. *Science Advances*, **3**(4); e1601939
- Liu, G., J. Ding, L. Qiao, A. Guo, B. P. Dymov, J. T. Gleeson, T. Hashimoto, and K. Saijo (1999). Polystyrene-Block-Poly(2-Cinnamoyl ethyl Methacrylate) Nanofibers–Preparation, Characterization, and Liquid Crystalline Properties. *Chemistry–A European Journal*, **5**(9); 2740–2749
- Maiyalagan, T., B. Viswanathan, and U. V. Varadaraju (2006). Fabrication and Characterization of Uniform TiO₂ Nanotube Arrays by Sol-Gel Template Method. *Bulletin of Materials Science*, **29**(7); 705–708
- Makhlof, A. and A. Barhoum (2018). *Emerging Applications of Nanoparticles and Architectural Nanostructures: Current Prospects and Future Trends*. Elsevier

- Matthews, J. A., G. E. Wnek, D. G. Simpson, and G. L. Bowlin (2002). Electrospinning of Collagen Nanofibers. *Biomacromolecules*, **3**(2); 232–238
- Mechanics Electronics Computer Corporation (2014a). Clip Spinneret. <http://www.mecc.co.jp/en/html/nanon/spinneret/clip.html>
- Mechanics Electronics Computer Corporation (2014b). Electrospinning Set Up. <http://www.bioeng.nus.edu.sg/nanobio/ESmachines/MECC.pdf>
- Mechanics Electronics Computer Corporation (2014c). Multi Jet Spinneret. <http://www.mecc.co.jp/en/html/nanon/spinneret/multijet.html>
- Medeiros, E. S., G. M. Glenn, A. P. Klamczynski, W. J. Orts, and L. H. C. Mattoso (2009). Solution Blow Spinning: A New Method to Produce Micro- and Nanofibers from Polymer Solutions. *Journal of Applied Polymer Science*, **113**(4); 2322–2330
- Meier, C. and M. E. Welland (2011). Wet-Spinning of Amyloid Protein Nanofibers into Multifunctional High-Performance Biofibers. *Biomacromolecules*, **12**(10); 3453–3459
- Melcher, J. R. and G. I. Taylor (1969). Electrohydrodynamics: A Review of the Role of Interfacial Shear Stresses. *Annual Review of Fluid Mechanics*, **1**(1); 111–146
- Mohammed, A. H. (2024). Study and Characterization of ZnO Nanoparticles Prepared by Switched Laser Nd:YAG. *Indonesian Journal of Material Research*, **2**(3); 73–78
- Namekawa, K., M. Morita, H. Ueda, K. Nakashima, T. Fujii, and K. Kuroda (2014). Fabrication of Zeolite-Polymer Composite Nanofibers for Removal of Uremic Toxins from Kidney Failure Patients. *Biomaterials Science*, **2**(5); 674–679
- Nayak, R., R. Padhye, L. Arnold, L. Wang, and R. Gupta (2012). Recent Advances in Nanofibre Fabrication Techniques. *Textile Research Journal*, **82**(2); 129–147
- Oberlin, A., M. Endo, and T. Koyama (1976). Filamentous Growth of Carbon through Benzene Decomposition. *Journal of Crystal Growth*, **32**(3); 335–349
- Okuda, T., K. Tominaga, and S. Kidoaki (2010). Time-Programmed Dual Release Formulation by Multilayered Drug-Loaded Nanofiber Meshes. *Journal of Controlled Release*, **143**(2); 258–264
- Ondarcuhu, T. and C. Joachim (1998). Drawing a Single Nanofibre over Hundreds of Microns. *Europhysics Letters*, **42**(2); 215–220
- O'Regan, B. and M. Grätzel (1991). A Low-Cost, High-Efficiency Solar Cell Based on Dye-Sensitized Colloidal TiO₂ Films. *Nature*, **353**; 737–740
- O'Regan, B., D. T. Schwartz, S. M. Zakeeruddin, and M. Grätzel (2000). Electrodeposited Nanocomposite n-p Heterojunctions for Solid-State Dye-Sensitized Photovoltaics. *Advanced Materials*, **12**(17); 1263–1267
- Pakravan, M., M.-C. Heuzey, and A. Ajji (2011). A Fundamental Study of Chitosan/PEO Electrospinning. *Polymer*, **52**(21); 4813–4824
- Pedicini, A. and R. J. Farris (2003). Mechanical Behavior of Electrospun Polyurethane. *Polymer*, **44**(22); 6857–6862
- Penide, J., J. Pou, F. Quintero, R. Comesana, F. Lusquiños, A. Riveiro, and M. Boutinguiza (2014). Laser Spinning: A New Technique for Nanofiber Production. *Physics Procedia*, **56**; 365–370
- Powell, H. M., D. M. Supp, and S. T. Boyce (2008). Influence of Electrospun Collagen on Wound Contraction of Engineered Skin Substitutes. *Biomaterials*, **29**(7); 834–843
- Quintero, F., J. Pou, R. Comesana, F. Lusquiños, A. Riveiro, and M. Boutinguiza (2007). Rapid Production of Ultralong Amorphous Ceramic Nanofibers by Laser Spinning. *Applied Physics Letters*, **90**(15); 153109
- Quintero, F., J. Pou, R. Comesana, F. Lusquiños, A. Riveiro, and M. Boutinguiza (2009). Laser Spinning of Bioactive Glass Nanofibers. *Advanced Functional Materials*, **19**(19); 3084–3090
- Radushkevich, L. V. and V. M. Lukyanovich (1952). Carbon Structure Formed under Thermal Decomposition of Carbon Monoxide on Iron. *Zhurnal Fizicheskoi Khimii*, **26**(1); 88–95
- Ramakrishna, S., K. Fujihara, W.-E. Teo, T.-C. Lim, and Z. Ma (2005). *An Introduction to Electrospinning and Nanofibers*. World Scientific, Singapore
- Rasouli, R. and A. Barhoum (2019). Advances in Nanofibers for Antimicrobial Drug Delivery. In *Handbook of Nanofibers*. Springer International Publishing, Cham, pages 733–774
- Rasouli, R., A. Barhoum, M. Bechelany, and A. Dufresne (2019). Nanofibers for Biomedical and Healthcare Applications. *Macromolecular Bioscience*, **19**(2); 1800256
- Rayleigh, L. (1879). On the Capillary Phenomena of Jets. *Proceedings of the Royal Society of London*, **29**(196–199); 71–97
- Rouaramadan, E. and A. A. Hasan (2013). Study of the Optical Constants of the PVC/PMMA Blends. *International Journal of Application or Innovation in Engineering & Management*, **2**(11); 240–243
- Schreuder-Gibson, H., P. Gibson, K. Senecal, M. Sennett, J. Walker, W. Yeomans, D. Ziegler, and P.-P. Tsai (2002). Protective Textile Materials Based on Electrospun Nanofibers. *Journal of Advanced Materials*, **34**(3); 44–55
- Simons, H. L. (1966). Process and Apparatus for Producing Patterned Non-Woven Fabrics
- Song, M. Y., D. K. Kim, K. J. Ihn, S. M. Jo, and D. Y. Kim (2004). Electrospun TiO₂ Electrodes for Dye-Sensitized Solar Cells. *Nanotechnology*, **15**(12); 1861–1865
- Stankus, J. J., J. Guan, and W. R. Wagner (2004). Fabrication of Biodegradable Elastomeric Scaffolds with Sub-Micron Morphologies. *Journal of Biomedical Materials Research Part A*, **70**(4); 603–614
- Steele, B. C. H. and A. Heinzl (2001). Materials for Fuel-Cell Technologies. *Nature*, **414**(6861); 345–352
- Su, Z., J. Ding, and G. Wei (2014). Electrospinning: A Facile Technique for Fabricating Polymeric Nanofibers Doped with Carbon Nanotubes and Metallic Nanoparticles for Sensor Applications. *RSC Advances*, **4**(94); 52598–52610
- Sutti, A., T. Lin, and X. Wang (2011). Shear-Enhanced Solution Precipitation: A Simple Process to Produce Short Polymeric Nanofibers. *Journal of Nanoscience and Nanotechnology*, **11**(10); 8947–8952
- Taylor, G. I. (1964). Disintegration of Water Drops in an Electric Field. *Proceedings of the Royal Society of London. Series A*,

- Mathematical and Physical Sciences*, **280**(1382); 383–397
- Taylor, G. I. (1969). Electrically Driven Jets. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, **313**(1515); 453–475
- Teo, W. E. and S. Ramakrishna (2006). A Review on Electrospinning Design and Nanofibre Assemblies. *Nanotechnology*, **17**(14); R89–R106
- Theron, A., E. Zussman, and A. L. Yarin (2001). Electrostatic Field-Assisted Alignment of Electrospun Nanofibres. *Nanotechnology*, **12**(3); 384–390
- Tucker, N., J. J. Stanger, M. P. Staiger, H. Razzaq, and K. Hofman (2012). The History of the Science and Technology of Electrospinning from 1600 to 1995. *Journal of Engineered Fibers and Fabrics*, **7**(2); 63–73
- Turky, A. O., A. Barhoum, M. Mohamed Rashad, and M. Bechelany (2017). Enhanced the Structure and Optical Properties for ZnO/PVP Nanofibers Fabricated via Electrospinning Technique. *Journal of Materials Science: Materials in Electronics*, **28**(23); 17526–17532
- Uludağ, H. (2014). Grand Challenges in Biomaterials. *Frontiers in Bioengineering and Biotechnology*, **2**; 43
- Wang, X., I. C. Um, D. Fang, A. Okamoto, B. S. Hsiao, and B. Chu (2005). Formation of Water-Resistant Hyaluronic Acid Nanofibers by Blowing-Assisted Electro-Spinning and Non-Toxic Post Treatments. *Polymer*, **46**(13); 4853–4867
- Wang, Y., S. Serrano, and J. J. Santiago-Aviles (2001). Electrostatic Synthesis and Characterization of $Pb(Zr_xTi_{1-x})O_3$ Micro/Nanofibers. *MRS Online Proceedings Library Archive*, **702**; U3.6.1–U3.6.6
- Wang, Y., S. Serrano, and J. J. Santiago-Avilés (2003). Raman Characterization of Carbon Nanofibers Prepared Using Electrospinning. *Synthetic Metals*, **138**(3); 423–427
- Yang, Y., X. Zhu, W. Cui, X. Li, and Y. Jin (2009). Electrospun Composite Mats of Poly[(D,L-Lactide)-Co-Glycolide] and Collagen with High Porosity as Potential Scaffolds for Skin Tissue Engineering. *Macromolecular Materials and Engineering*, **294**(9); 611–619
- Yokoyama, Y., S. Hattori, C. Yoshikawa, Y. Yasuda, H. Koyama, and T. Takato (2009). Novel Wet Electrospinning System for Fabrication of Spongiform Nanofiber Three-Dimensional Fabric. *Materials Letters*, **63**(9–10); 754–756
- Yoo, H. S., T. G. Kim, and T. G. Park (2009). Surface-Functionalized Electrospun Nanofibers for Tissue Engineering and Drug Delivery. *Advanced Drug Delivery Reviews*, **61**(12); 1033–1042
- Yu, D. G., J. J. Li, G. R. Williams, and M. Zhao (2018). Electrospun Amorphous Solid Dispersions of Poorly Water-Soluble Drugs: A Review. *Journal of Controlled Release*, **292**; 91–110
- Yuan, X., Y. Zhang, C. Dong, and J. Sheng (2004). Morphology of Ultrafine Polysulfone Fibers Prepared by Electrospinning. *Polymer International*, **53**(11); 1704–1710
- Yuya, P. A., Y. Wen, J. A. Turner, Y. A. Dzenis, and Z. Li (2007). Determination of Young's Modulus of Individual Electrospun Nanofibers by Microcantilever Vibration Method. *Applied Physics Letters*, **90**(11); 111909
- Zeleny, J. (1935). The Role of Surface Instability in Electrical Discharges from Drops of Alcohol and Water in Air at Atmospheric Pressure. *Journal of the Franklin Institute*, **219**(6); 659–675
- Zhang, C., X. Yuan, L. Wu, Y. Han, and J. Sheng (2005). Study on Morphology of Electrospun Poly(Vinyl Alcohol) Mats. *European Polymer Journal*, **41**(3); 423–432
- Zhang, K., X. Wang, D. Jing, Y. Yang, and M. Zhu (2009). Bionic Electrospun Ultrafine Fibrous Poly(L-Lactic Acid) Scaffolds with a Multiscale Structure. *Biomedical Materials*, **4**(3); 035004
- Zhao, S., X. Wu, L. Wang, and Y. Huang (2004). Electrospinning of Ethyl-Cyanoethyl Cellulose/Tetrahydrofuran Solutions. *Journal of Applied Polymer Science*, **91**(1); 242–246
- Zucchelli, A., D. Fabiani, C. Gualandi, and M. L. Focarete (2009). An Innovative and Versatile Approach to Design Highly Porous, Patterned, Nanofibrous Polymeric Materials. *Journal of Materials Science*, **44**(18); 4969–4975