Nanofiber Membranes for Medical, Environmental, and Energy Applications

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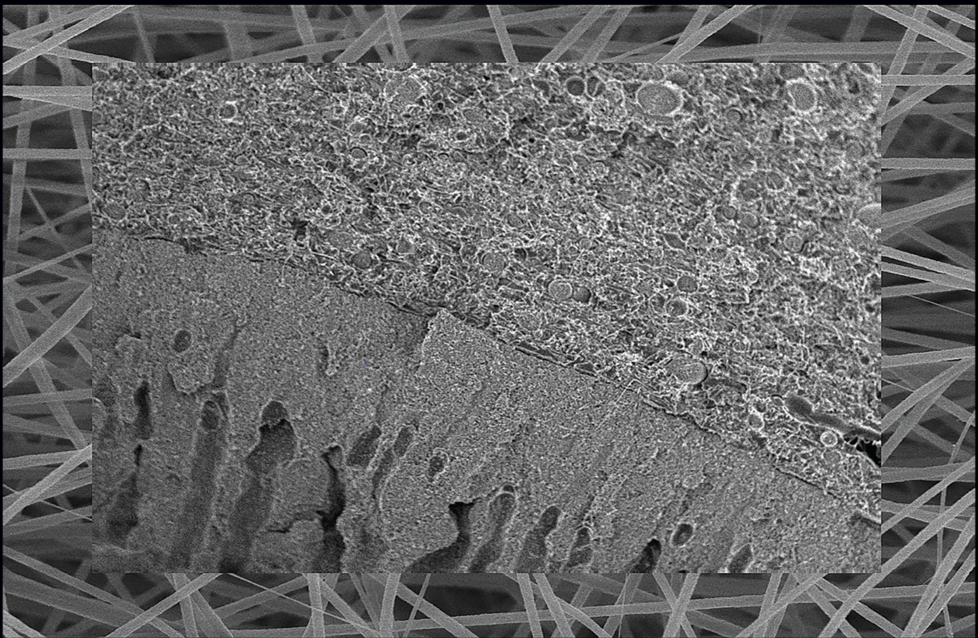

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Preface

This book consists of 13 chapters with topics related to nanofiber membrane for medical, environment and energy applications. The contributors come from Asian and European countries, including Malaysia, Singapore, Turkey, Iran, and the United Kingdom. There are also contributions from Canada. The authors are experts in the development of nanofibers and membranes technology for various applications.

In particular, this book gathers numerous promising nanofiber membranes for improving and enhancing the current technologies used in drug delivery, wound healing, tissue engineering, water and wastewater treatment and purification, and fuel cells. The chapters place emphasis on the nanofiber membrane fabrication techniques and characterizations that suit the proposed applications and the way forward of the nanofiber membranes for commercial use.

This book has been separated into three major topics; medical, environmental, and energy applications. The arrangement of the content of the book is as follows.

The general information of nanofibers-based technology development for medical, environment especially water and wastewater treatment, and energy applications is presented by Chapter 1, entitled "Electrospun Polymeric Nanofiber: Production, Characterization and Application." This chapter discusses the topic to give a clear picture on the suitable technique to produce the nanofibers that meet the demand in terms of properties and performance according to applications.

It follows by Chapters 2 through 4 which cover nanofibers-based technology applications for medical. A thorough discussion to the related topic is presented by three chapters entitled "Electrospun Antimicrobial Membranes-functionality and Morphology" (Chapter 2), "Nanofiber Electrospun Membrane Based on Biodegradable Polymers for Biomedical and Tissue Engineering Application" (Chapter 3), and "Electrospun Collagen Nanofiber Membranes for Regenerative Medicine" (Chapter 4).

Due to the recent accelerated interest in highly potential nanofibers-based technology application in water and wastewater, Chapters 5 through 9 only emphasizes these particular applications. Five chapters covers this topic, which including "Nanofiber Membranes for Oily Wastewater Treatment" (Chapter 5), "Electrospun Nanofibrous Membranes for Membrane Distillation Process" (Chapter 6), "Nanofibrous Composite Membranes for Membrane Distillation" (Chapter 7), "Electrospun Nanofiber Membranes as Efficient Adsorbent for Removal of Heavy Metals" (Chapter 8), and "Surface Functionalized Electrospun Nanofibers for Removal of Toxic Pollutants in Water" (Chapter 9).

Meanwhile Chapters 10 through 13 provide the topic of the use of nanofibers in energy applications. There are four chapters provide the discussion on the said topic which are "Nanofiber Membranes for Energy Applications" (Chapter 10), "Electrospun Nanocomposite Polymer Electrolyte Membrane for Fuel Cell Applications" (Chapter 11), "Proton Transport Mechanisms in Nanofibers Ion Exchange Membrane: State of the Art and Perspectives" (Chapter 12), and

“Fabrication of Mesoporous Nanofiber Networks by Phase Separation-Based Methods” (Chapter 13).

The editors would like to highlight that apart from the growing number of research publications in membrane science and technology for the solutions of the environmental problems, the advantages of the membrane in nanofibers form is foreseen a commercially able material. With about 500 pages, this book offers the recent findings of research works from the established researchers specialized in the nanofiber membrane technologies and will definitely give full of satisfaction to the users. This book possesses its own uniqueness because established researchers from around the globe contributed to the chapters, each based on their recent research findings. Thus readers could find the most recent nanofiber membrane materials that are appropriate for medical, environment and energy applications. This could also give a clear picture on the trend of advanced materials as the way forward for the mentioned applications.

The editors would like to express their sincere thanks to all authors and co-authors for their kind support, encouragement, and their understanding of the amount of time it has taken for the book’s writing. Sincere thanks also go to Barbara Knott and Danielle Zarfati from Taylor and Francis Group for their kind assistance from the beginning until the end of the publication process of this book.

Ahmad Fauzi Ismail

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Editors

Professor Dr. Ahmad Fauzi Ismail is the founder and first director of Advanced Membrane Technology Research Centre (AMTEC). His research interest are in development of polymeric, inorganic and novel mixed matrix membranes for water desalination, waste water treatment, gas separation processes, membrane for palm oil refining, photocatalytic membrane for removal of emerging contaminants, development of haemodialysis membrane and polymer electrolyte membrane for fuel cell applications. His research has been published in many high impact factor journals. He also actively authored many academic books in this field, which were published by reputable international publishers. He is the author and co-author of over 600 refereed journals. He has authored 6 books, over 50 book chapters and 4 edited books, 6 patents granted, patents with the patent number of US Patent (6,521,025 B1 and WO00/27512), and has 14 patents pending. His h-index is 66 with cumulative citation of over 19,300. He won more than 150 awards national and internationally. Among the most prestigious award won is the Merdeka Award for the Outstanding Scholastic Achievement Category at 4th September 2014, Malaysia's Rising Star Award 2016 for Frontier Researcher category at 1st November 2016, and Malaysia's Research Star Award 2017 on 5 October 2017, Malaysia's Research Start Award 2018. Recently, he was appointed as UNESCO chair on groundwater arsenic within the 2030 Agenda for Sustainable Development. He is the chairman of Academy of Sciences Malaysia (Southern Region), fellow of the Academy of Sciences Malaysia, chartered engineer in the UK (CEng) and a fellow of the Institution of Chemical Engineers (FIChemE). Ahmad Fauzi also served on the Editorial Board Members of Desalination, Journal of Membrane Water Treatment, Jurnal Teknologi, Journal of Membrane Science and Research, Journal of Membrane and Separation Technology and as an advisory editorial board member of Journal of Chemical Technology and Biotechnology. He is involved extensively in R&D&C for national and multinational companies related to membrane-based processes for industrial application and currently have two spin off companies. He is the founder of Advanced Membrane Technology Research Centre (AMTEC) and now recognized as Higher Education Centre of Excellence (HICoE). Currently Ahmad Fauzi is the deputy vice chancellor of research and innovation, UTM.

His active participation in scientific research and development has also been exhibited by the recipient of research grant sponsored by government and non-government bodies. Until now, the total research grant secured is USD 11,105,360.00. Among the most recent project was Long-term Research Grant Scheme (LRGS) and European Universal Grant with the budget allocation of USD 1,466,280.00 and USD 326,535.00, respectively. Petronas Research has allocated USD 1,957,347.00 whereas SIME Darby allocated USD 247,460.00 for joint research programs with AMTEC. In 2012, he was awarded the Best Research Project award for his *Fundamental Research Grant Scheme* (FRGS) project by the Ministry of Education. In 2013, Malaysia Toray Science Foundation awarded him with a special award for his involvement and contribution in research activities and innovations. Ministry of

Education unanimously awarded him with the Innovative Action Plan for Human Capital Development Tertiary Level award.

Since 2007 until now, he has successfully generated income of about USD $1,000,000 from his invention and innovation related to membrane technology. The Innovation and Product Commercialization Award has been awarded to Fauzi in the Nation Academic Award Ceremony 2013 in recognition to his remarkable commercialization activities.

Professor Nidal Hilal is a chartered engineer in the United Kingdom (CEng), a registered European engineer (Euro Ing), an elected fellow of both the Institution of Chemical Engineers (FIChemE), and the Learned Society of Wales (FLSW). He received his bachelor's degree in chemical engineering in 1981 followed by a master's degree in advanced chemical engineering from Swansea University in 1986. He received his PhD degree from Swansea University in 1988. In 2005 he was awarded a Doctor of Science degree (DSc) from the University of Wales in recognition of an outstanding research contribution in the fields Scanning Probe Microscopy and Membrane Science and Technology. He was also awarded, by the Emir of Kuwait, the prestigious Kuwait Prize of Applied Science for the year 2005.

His research interests lie broadly in the identification of innovative and cost-effective solutions within the fields of nano-water, membrane technology, and water treatment, including desalination, colloid engineering and the nano-engineering applications of AFM. He has published 7 handbooks, 73 invited book chapters and around 450 articles in the refereed scientific literature. He has chaired and delivered lectures at numerous international conferences and prestigious organizations around the world.

He is the editor-in-chief of the international journal *Desalination*. He sits on the editorial boards of a number of international journals, is an advisory board member of several multinational organizations, and has served on/consulted for industry, government departments, research councils, and universities on an international basis.

Associate Professor Dr. Juhana Jaafar graduated with a BEng (Chemical Engineering) from Universiti Teknologi Malaysia in 2004. She was then granted with National Science Fellowship under Ministry of Higher Education (MOHE) to pursue her MSc in (Gas Engineering) from Universiti Teknologi Malaysia. In 2011, she graduated with a PhD in Gas Engineering from the same university specializing in Advanced Membrane Manufacturing for Energy Application. She has started her academic career at UTM in 2007. Currently she is a senior lecturer of, School of Chemical and Energy Engineering, Faculty of Engineering. She also holds a position as deputy direct of Advanced Membrane Technology Research Centre (AMTEC).

Her outstanding outputs in research were evident from her receiving distinguished awards at national and international levels including Asian Invention Excellent Award, 28th International Invention, Innovation and Technology Exhibition (ITEX 2017), Gold Medal, International Invention, Innovation and Design Johor 2017 (IIIDJ 2017), Most Distinguished Award – Higher Education International Conference, and Innovation Expo of Institute of Higher Education (PECIPTA 2013), Best of the Best awards at the Malaysian Technology Expo (MTE 2008) and Double Gold Medal in British Invention

Show (BIS 2008). Dr. Juhana is also active in writing for scientific publication in high-impact factor in international and national journals. To date, she has published more than 170 papers in ISI-indexed journals with H-index of 20. Until now, she had led 12 research grants and is a member of more than 60 research projects including the Long-Term Research Grant Scheme, which was awarded by Ministry of Higher Education, Malaysia, with the budget allocation of USD $1.5 million and International European Grant with the allocation of USD $700,000. Owing to her outstanding achievement in research, she has been selected as the UTMShine recipients for the year 2016.

She is actively involved with various committees at the national level, including the co-secretary general of Malaysia Membrane Society (MyMembrane), the secretary general of the National Congress on Membrane Technology 2016, steering committees for National Science Challenge 2017, International Workshop on Nanocomposite Materials for Photocatalytic Degradation of Pollutants: Advanced Opportunities for New Applications 2015, International Conference on Membrane Science and Technology 2013, Nanomaterials Technology Specialized Conference 2012, and the International Conference on Membrane Science and Technology 2009. She is also the organizing/scientific committee of 6th International Conference on Material Science and engineering technology (ICMSET 2017), International Conference on Membrane Technology and its Applications (MemSep-2017) and International Conference on Membrane Science and Technology (MST 2015).

Dr. Juhana has received several awards and recognition at the international level. Recently, she received a scholarship from AUNSEED-Net for Short-term Research Program in Japan and Short-term visit program in ASEAN country. She also has obtained a scholarship from Meiji University under the International Exchange Program 2017. She has also been listed in the Who's Who in the World, 33rd Edition 2016.

Dr. Chris J. Wright is a reader in bioprocess engineering in the College of Engineering at Swansea University. His research is focused on the biological interface and he has developed advanced characterization techniques alongside membrane fabrication in order to control bioprocess systems. His research laboratory, the Biomaterials, Biofouling and Biofilms Engineering Laboratory (B^3EL) uses electrospinning and melt electrospinning to create novel fibrous materials for application within process industries, medicine and agriculture. The underlying themes of this research are improved functionality of fibers and manufacture at scale.

Dr. Wright received his BSc in Applied Biology from the University of Wales Cardiff and completed his PhD at Swansea in Biochemical Engineering sponsored by The Brewing Research Foundation International in 1996. In 2001 he was awarded an Engineering and Physical Sciences Research Council (EPSRC) Advanced Research Fellowship. This prestigious five-year award enabled him to establish an internationally recognized research group exploiting the capabilities of atomic force microscopy (AFM) for the characterization and control of microbial interactions.

From 2006 to 2011 he was portfolio director for chemical engineering within the College of Engineering at Swansea University, and he established Medical Engineering and Environmental Engineering degree courses. He was also the director of the Multidisciplinary Nanotechnology Centre (MNC), associate director of the

Centre for Complex Fluids Processing, and founding executive member of the Centre for NanoHealth at Swansea University.

Dr. Wright's has been at the forefront in the development of AFM probe methods to measure interactions between biocolloids and surfaces. This featured the first-ever AFM cell probe in 1998 that allowed the direct measurement of the forces involved in cell-surface interactions. His research group has subsequently applied this technique for the study of bacterial, fungal and mammalian cells as well as protein-protein interactions. He has also established AFM techniques for the nanoscale characterization of the mechanical properties of biofilms and biofouling at separation membranes. To allow the translation of his research Dr. Wright has created two spinout companies, Membranology and ProColl; these companies are applying membrane technology and novel collagen fibrous materials, respectively.

Dr. Wright has over 120 international publications, 15 book chapters, and is editor of 2 books within the research area. He is on the editorial board of three international journals. His research has been sustained through major grants (in excess of £9M) from across the UK research councils, Royal Society, Royal Academy of Engineering, European funding, charity, and industry.

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1 Electrospun Polymeric Nanofibers

Production, Characterization and Applications

Ali Moslehyani, Juhana Jaafar, Ahmad Fauzi Ismail, and Takeshi Matsuura

CONTENTS

1.1 INTRODUCTION

There are many different methods for nanofibrous membrane fabrication, which include melt fibrillation, island-in-sea methods, gas jet techniques, nanolithography, and self-assembly. Low cost, high production rate, and different modes of assembly are the benefits of the nanofibrous membrane. All high molecular weight polymers soluble in a solvent can be electrospun alone or by mixing with any type of miscible nanoparticles to produce polymeric nanofibrous membranes [1]. They can be fabricated from natural polymers, polymer blends, nanoparticle- or drug-impregnated polymers, and ceramic precursors in multiple structures such as beaded, ribbon-shaped, porous, and core-shell fibers [2,3].

The electrospinning process starts with the extrusion of a polymeric solution through a spinneret syringe needle (Figure 1.1). The difference between electrospinning and hollow fiberspinning is that the hollow fiber technique requires air or mechanical devices to create the extrusion force, while electrospinning needs a high voltage to charge the excluded solution. The repulsive force generated at the polymer solution surface then overcomes the surface tension of the solution and a jet erupts from the tip of the spinneret accelerating toward the region of lower electrical potential. While the solution jet is traveling through a distance, the solvent evaporates when the entanglement of the polymer chains prevents the jet from breaking up

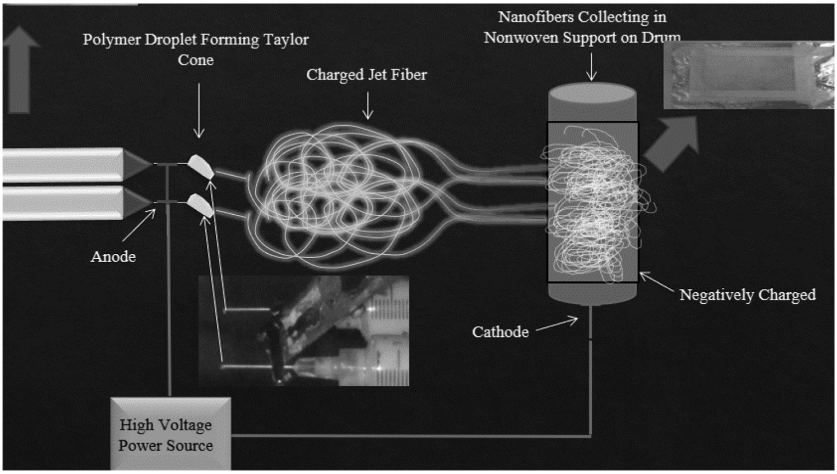

FIGURE 1.1 Electrospinning procedure.

during fiber formation. Generally, a grounded plate or a drum collector is used to collect the fibers from the spinneret [4–7].

The technology of electrospinning was invented in 1902 in the United States of America, which was however forgotten until 1990s. Then, during the last three decades researchers began new studies of electrospinning of nanofibers and their characterization among 200 universities and research institutes worldwide. The number of patents on new spinning methods and applications steeply increased and many companies such as e-Spin Technologies, Nano Technics, and KATO Tech are competitively involved to reap the unique benefits offered by electrospinning, while companies such as Donaldson and Freudenberg have been using nanofibers for air purification products for 20 years. The ability to form porous electrospun nanofibers means that the surface area of the fiber mesh can be increased tremendously [7–10].

Depending on the volatility of the solvent, porous nanofiber filaments are formed during electrospinning. Blending of dissimilar polymers is another way to fabricate porous filaments, by removing one polymer component with solvent while the other component remains insoluble [11–13]. Trajectory of the polymer solution jet is usually non uniform, which results in the formation of a nonwoven mesh. However, more ordered assembly of nanofibers is possible by managed fiber formation. Numerous approaches have been applied that produce aligned nanofibers with many degrees of order by controlling the electric field between the needle and collector plate, using a rotating mandrel, or the combination of both [5,14–16]. It has been demonstrated that a drum collector rotating at high speed can collect aligned fibers. Using a couple of conducting electrodes can also generate aligned fibers among the electrodes. To form a tubular scaffold, electrospun nanofibers were deposited on a spinning tube and the layer of nanofibers was pulled out consequently [17,18]. Another way of producing aligned nanofibers can be to use support electrodes to make an electric field profile that affects the flight of the electrospinning jet. With such versatility,

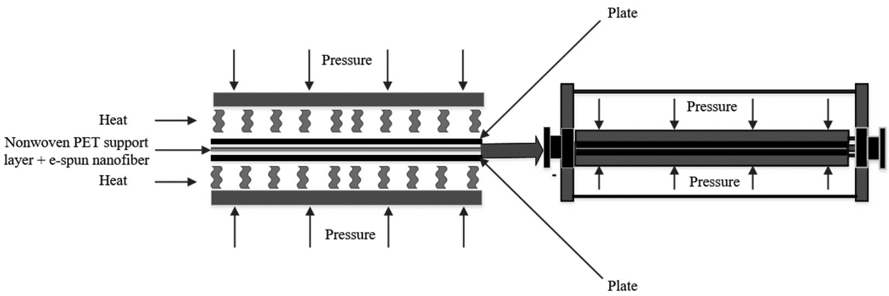

FIGURE 1.2 Illustration of the hot-pressing method.

nanofibrous membranes can be investigated for use in many applications. Presently, most tests use nonwoven fiber meshes made out of smooth fibers. Ceramic nanofibers derived from nonwoven electrospun fiber meshes have opened up many opportunities for application in different technologies. Heat-pressed nonwoven meshes have been demonstrated to be useful for high pressure applications (Figure 1.2). Therefore, the adaptability of electrospun fibers is clear and demonstrated by the proven results and current ongoing experimental studies in areas such as biotechnology, environmental engineering, healthcare, energy storage and generation, defense, and security [19–22].

1.2 ADVANTAGE OF USING ELECTROSPUN NANOFIBROUS MEMBRANE

The useful properties of electrospun nanofibrous membranes such as high absorbency, porosity, nanoscale interstitial space interconnectivity, and large surface area have meant that they have been used extensively in control of biological processes. Nanofibrous membranes with a nonwoven support have been used in various industrial biotechnology and environmental dynamic systems, because ligand molecules, bio-macromolecules, or even cells can be attached or hybridized within the nanofiber mat. Some of the examples are applications in protein filtration and wastewater purification by adsorptive barrier, or adsorptive catalyst mats, and, in the future, diagnostics and chemical detection as smart barriers [23,24].

Electrospun nanofibers have been fabricated in different sizes (50–500 nm) for dust removal in air purification by either adsorptive or physical filtration. Nanofibrous membranes have been shown to eliminate many types of contaminants from wastewater such as heavy metals, virus, and pharmaceutical byproducts. Interestingly there was no pore blockage due to the entrapment of particles inside the nanofiber mat, so the nanofibrous barrier could be efficiently reused after cleaning, which enabled the use of nanofibrous membranes during dynamic operation and allowed their use prior to many wastewater purification systems such as microfiltration, ultrafiltration, nanofiltration, and forward or reverse osmosis. These types of nanofibrous membranes are usually called adsorptive barriers that selectively capture specific target molecules by the incorporation of adsorbents in the nanofibers. Adsorptive barriers have been applied for protein and bio-products filtration in biotechnology [11,25].

Environmental applications for organic waste removal are another interesting use of adsorptive nanofiber membranes which depends on their great capacity to adsorb organic compounds, especially when the surfaces of polymeric nanofibers such as those made from cellulose, Polyvinylidene fluoride (PVDF), Polyethersulfone (PES), Polyethylenimine (PEI), Polysulfone (PSf) are modified. Modified cellulose nanofibers have been used for the purification of albumin and the detection of IgG molecules with a significant volume, which is higher than that of commercial membrane. Water and wastewater contamination has become a serious global issue, where heavy metals such as Hg, Pb, Cu, Cd, and others are one of the most important classes of inorganic pollutants [26–31]. Distribution of heavy metals in the environment is mainly attributed to the release of metal containing wastewaters from industries. For example, copper smelters release high amounts of Cd, one of the most mobile and toxic metals among the trace elements, into nearby streams It is not possible to completely remove some types of environmental contaminants such as metals by conventional water purification methods. Hence, adsorptive membranes will play a critical role in wastewater treatment to eliminate (or recycle) heavy metal ions in the future. Polymeric nanofibers, embedded with hydrated alumina/alumina hydroxide or iron oxides, were proven to be very effective for such purposes by removing toxic heavy metal ions such as As, Cr, and Pb via adsorption/chemisorption and electrostatic attraction mechanisms. Water quality level is also very sensitive to organic pollutants. Even though the concentration of the organics is usually no more than 1% of the pollutants in rivers, they tend to deplete its dissolved oxygen, making the water unable to sustain life. While the changes and pathways of metals in the environment have been studied to some extent, much less information is available on most commercial organic products due to their complex configurations [2,32–37]. Again, adsorptive membranes provide another method for eliminating organic molecules from wastewater. For example, β-cyclodextrin is a cyclic oligosaccharide composed of seven glucose units and a stereospecific toroidal structure. Due to its unique structure with a hydrophobic interior and hydrophilic exterior it can capture hydrophobic organic molecules from water by forming an inclusion complex. β-cyclodextrin has been incorporated into a poly(methyl methacrylate) nanofibrous membrane using a physical mixing method to develop an adsorptive membrane for organic waste removal [29,38–41]. Electrospun nanofibers have also received great attention for sensor applications because of their unique high surface area. This is one of the most desirable properties for improving the sensitivity of conduct metric sensors because a larger surface area will absorb more of a gas to be analyzed and change the sensor's conductivity more significantly. Nanofibers modified with a semiconductor oxide such as MoO_3, SnO_2, or TiO_2 show an electrical resistance that is sensitive to harmful chemical gases like ammonia and nitroxide. Single polypyrrole nanofibers containing SnO_2 were studied as biosensors for detecting biotin-labeled biomolecules such as DNA. Specific binding of the biomolecules to the nanofibers changes the electrical resistance of a single nanofiber. A fluorescent polymer, poly(acrylic acid)-poly(pyrene methanol), PAA-PM, was used as a sensing material for the detection of organic and inorganic waste. The fluorescence is quenched by adsorbed metal ions Fe^{3+} or Hg^{2+} or 2,4-dinitrotoluene (DNT) on the nanofiber surfaces [36,42–53].

1.3 POTENTIAL OF ELECTROSPUN NANOFIBROUS FOR WATER TREATMENT

Water purification requires several sequential steps to make collected water drinkable. These steps include removal of particulate matters, pathogens, and selected ions. Regarding the particulate removal, electrospun nanofibers are suitable for use as a size exclusion filter for particles of more than a few microns since the pore size of nanofiber ranges from submicron to few microns. A comprehensive study on the micro particles rejection using a heat-treated polysulfone (PSU) electrospun nonwoven membrane with a bubble point that corresponds to 4.6 μm showed that full flux recovery was possible for the particle size 7, 8, and 10 μm with more than 99% separation factor. Full flux recovery was also reported for 5 μm size particles with a separation factor greater than 90% using heat treated polyvinylidene fluoride (PVDF) membrane [54–58]. However, flux recovery was incomplete for particle sizes less than 3 μm. Examination of the cross-section of the membrane showed that for larger particles (more than 5 μm), the membrane acted as a size exclusion filter or screen filter with the particles trapped on the surface of the membrane. The flux could be recovered by stirring the solution inside the membrane module due to the low adhesion force between the particles and the fiber surface [58–62]. Another objective for the process of water treatment is the removal of heavy metals, which is a serious issue in many developing countries due to the rapid industrialization and impact of mining operations. Such heavy metal ions cannot be filtered out by microfiltration as the ions are too small. Instead of size exclusion, surface adsorption-based electrospun membrane has been developed. The high surface area of electrospun nanofiber meshes makes this technique suitable as more functional groups can be exposed on its surface. Open and interconnected pores formed by overlapping nanofibers allow the feed solution to pass through it. Arsenic (As) compounds are known as poisonous and cancer causing agents which are increasingly contaminating groundwater [63,64]. Chitosan electrospun nanofibers (ICS-ENF) modified by the incorporation of iron oxide were fabricated for the purpose of removing the trace amount of these arsenics from contaminated water. ICS-ENF was found to remove more than 90% of As under acidic to neutral conditions (pH 4.3–7.3). Thus its performance was better than pristine chitosan (CS) electrospun membrane which could adsorb As only little at neutral pH. When the pH was increased to 7.3, there was no adsorption of As even for ICS-ENF membrane. Adsorption by the nanofibrous membrane is dependent on the positive charge on its surface which interacts with the negatively charged As. At high pH, the surface charge of the electrospun nanofibrous membrane may turn negative and this will repel As ions, leading to their drop in adsorption capacity. In countries where there is limited available fresh water from the land, alternative source of water may come from the sea or from recycling waste water. These require technology that is able to separate salt and ions from the water source. While there is a well-established industrial purification technology such as reverse osmosis, other emerging technologies such as membrane distillation and ultra/nano-filtration are being tested with the hope of bringing down costs [65–72]. For ultrafiltration (0.1–0.01 μm) and nanofiltration (0.01–0.001 μm), the pore size of the electrospun membrane is too large to use without any modifications. Instead, the electrospun membrane can function as a supporting substrate to hold the separation layer as a thin film composite membrane. Whether the composite membrane is used for ultrafiltration or nanofiltration is dependent on the coated separation layer. High porosity and small fiber diameter of the electrospun membrane makes it an excellent supporting substrate as it gives a larger effective separation area (separation surface without underlying obstruction). Nano- and ultrafiltration membrane using electrospun membrane will theoretically give it a higher flux compared to other conventional membranes. To demonstrate effectiveness of electrospun thin film composite membrane in salt water purification, polyamide 6 nanofibers electrospun on polypropylene/polyethylene bio-component spun bond nonwoven fabric were used as the supporting substrate for interfacial *in-situ* polymerization of piperazine/trimesoyl chloride or m-phenylenediamine (MPD)/trimesoyl chloride, which function as the separation layer. An average rejection rate of 97.4% $CaCl_2$ and 96.3% NaCl was recorded for thin film nanofibrous composite (TFNC) membrane of MPD-Triethylamine (TEA)-Synferol AH (Sy-AH). Pure water flux of the TFNC was 22.5 L/m^2h while permeate flux of salt water was 12.5 L/m^2h. Using seawater, the TFNC membrane was able to retain more than 98% of the salt ions after three rounds of recirculation through the membrane [73–77].

Membrane distillation works by having a membrane to separate the salty water and pure water (permeate). There are a few parameters that affect the rate and efficiency of membrane distillation. First, there must be a temperature gradient between the feed side and permeate side. Traditionally, the separation layer is relatively thick so that heat conduction is limited from the feed to permeate, thus maintaining an optimal temperature gradient. The porosity, pore size, and tortuosity also affect the ease of water vapor passing through the membrane to form permeate. For an electrospun membrane to be used in membrane distillation, it must be able to maintain a separation between the feed and permeate water. Thus, a super hydrophobic membrane material is required [4,56,78–82]. Comparative tests on electrospun nanofibrous membrane and commercially available membrane showed that the liquid entry pressure (LEP) of electrospun PVDF membrane is less than 0.64 bar compared to 9 bar of commercial PTFE membrane. Electrospun PVDF membrane showed higher flux at a crossflow velocity of 80 mm/s than the PTFE and other commercial membranes. At a salinity lower than 50 g/kg, the thinner membrane has greater permeability and this is where the electrospun membrane has an advantage [78,82–87]. However, at higher salinity, flux for the nanofibrous membrane drops quickly while the PTFE membrane showed little difference. To increase the hydrophobicity of the membrane and maintain salt separation for longer duration, the surface of PVDF nanofibers was modified by coating silver nanoparticles through electroless silver-plating, followed by coating of membrane showed super hydrophobicity with a contact angle of 153° and water sliding angle below 10°. The flux of the membrane 32 L/m^2h was almost unchanged from the unmodified PVDF nanofibrous membrane and could be kept constant for the test duration of 8 h. Instead of super hydrophobic treatment of the surface, a commonly known super hydrophobic material polytetrafluoroethylene (PTFE) was used for fabrication of nanofibrous membrane. Since PTFE is difficult to be dissolved in most solvents, a suspension of PTFE fine particles in water was blended with water soluble polyvinyl alcohol (PVA). The PVA with PTFE particles was electrospun and the PVA component was removed through sintering up to 380°C for 30 min [4,88–93]. At this temperature the PTFE particles melted and fused together to form an interconnected nanofibrous network of PTFE. The resultant membrane showed a water contact angle of 156.7°. When tested for vacuum membrane distillation, a pure water flux of 15.8 kg/m^{2}h and a stable salt rejection of more than 98% for 10 h were recorded [85,94–96].

1.4 FUTURE PROSPECTIVE OF ELECTROSPINNING NANOFIBROUS MEMBRANE

Most of the nanofibrous composite membrane fabrication is currently based on an electrospinning approach with several weaknesses, such as difficulty of *in-situ* deposition of nanofibers, necessity for specialized equipment, low throughput, conducting targets, and high voltage. In addition, the electrospun nanofibrous mats have low mechanical strength due to the irregular and uncontrolled orientation of their component nanofibers and their low crystallinity. Therefore, more research on electrospinning is required to overcome these weaknesses. For example, nanofibrous synthesis throughput can be increased by further improvement of multi-needle and needleless electrospinning methods [39,97–102].

Recent developments in nanofiber electrospinning have meant that the application of the technology is moving at fast pace. Literature review shows that a large number of papers have been published on innovative production methods and this continues. However, to move beyond the current state of nanofibrous syntheses and applications toward technology maturation in commercial and industrial contexts, we need to address and overcome several challenges. First, it is imperative to standardize the newly developed synthetic methods, and second to bring these methods to a high engineering level such as physical properties to obtain the suitable and novel approaches of nanofibrous configurations including inter-fiber adhesion, smaller fiber dimension, and fiber surface modification. Nanofibers of more advanced configurations, such as core-shell, multilayer, and multicomponent nanofibers, may be prepared through methods similar to co-axial electrospinning [99,103–107].

Combining nanofibrous synthesis with other techniques, such as heat treatment, plasma treatment, chemical grafting, and control of fiber arrangement, is adaptable to further improve the surface properties of nanofibers. Eventually, the development of integrated nanofibrous synthesis strategies which are able to offer the best production procedures, such as the advanced nanofibrous structures of co-axial electrospinning, the high throughput of centrifugal jet spinning, and the *in situ* nanofibrous deposition of solution blow spinning, is highly desirable and should be the ultimate goal in the synthesis of nanofibers. Further, moving beyond synthesis, the next challenge is the identification of applications, those for which nanofibers are capable of revolutionizing a current practice. Nanofiber applications can be summarized in three important fields: energy, water, and healthcare. Most of these areas of application are still at the stage of emergence. In the case of energy application, despite the fact that nanofiber-based energy storage devices have demonstrated enhanced electrochemical properties and cycling performance, the potential of nanofiber-based technology in the area has not been fully exploited [108–113].

In biotechnology and environmental engineering, it is important to note that there are various efficient methods applicable for separation and purification, which include chemical precipitation, electrochemical processes, ion exchange, adsorption, and membrane filtration. Membrane adsorption (MA) combines the advantages of both adsorption and membrane filtration, offering an alternative option for effluent treatment. In particular, MA by electrospun adsorptive nanofiber membranes (EANMs) looks promising due to EANM's high permeation rate and adsorption capacity, and the possibility of their reuse over multiple times via appropriate desorption. For this reason, EANMs have attracted much interest recently as one of the most efficient techniques for biotechnological and environmental engineering via low operation cost. However, the use of suitable and compatible adsorbent particles is the most challenging parameter in the preparation of highly efficient EANMs, which needs more investigation [114–117].

Healthcare has a massive interest in the nanofibrous electrospinning process for both wound dressing and tissue engineering, since nanofiber mats are one of the most attractive options for helping the renewal of different kinds of tissues and cells. While the relationship between a wide range of nanofibrous supports and cells has been studied, the application of this research needs further proof-of-concept in terms of proliferation, cellular adhesion, and differentiation within the 3D structure of the electrospun mat. Additional analysis needs to be considered for the changes in cellular behaviors that are influenced by the topographical signals delivered by the nanofibrous supports. Obviously, more general *in vivo* investigations in human clinical trials are needed to demonstrate the influences and importance of nanofibrous process in biomedical engineering and healthcare [39,118–120].

1.5 CONCLUSIONS

Electrospinning is an old technology, which has been existing in the literature for more than 60 years. Although it is still immature, electrospinning is thought to be the best possible method for the fabrication of continuous nanofibers. A comprehensive as well as state-of-the-art review on electrospinning together with the applications of polymer nanofibers produced by this technique was made by this chapter. Relatively few polymers have been electrospun into nanofibers until now. Moreover, the understanding of the electrospinning process, the characterization of nanofibers, and the exploration of nanofiber applications specifically as nanocomposites seem to be very limited. Extensive researches and developments in all these three areas are required in the future.

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