

REVIEW ARTICLE

State-of-the-art of electrospun nanocomposite nanofibers and membranes with carbon nanoparticles—Prevailing progressions

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ABSTRACT

This state-of-the-art overview emphasizes electrospinning technique and resulting electrospun nanofibers and nanofibrous membranes. Consequently, the electrospinning method as well as the formation and features of the electrospun nanofiber/membrane nanomaterials have been described. Properties of the electrospun nanofibers have found to be enhanced several folds through the incorporation of carbon nanoparticles in the nanofibers. Important properties and utilizations of carbon nanocomposite electrospun nanofibers were seemed to be affected by nanoparticle amount and dispersal. Importantly, diameter, microstructure, and physical features (thermal, mechanical, conductive, etc.) of the nanofibers and resulting membranes can be affected by the nanofiller behavior. The high performance electrospun nanofibers have been used to form efficient nanocomposite nanofibrous membranes. Sequentially, the electrospun nanocomposite nanofibrous membranes have been applied in technical membrane applications.

Keywords: electrospinning; nanofibers; polymer; nanocomposite; membrane

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1. Introduction

Nanofibers, especially polymer structured nanofibers, are one dimensional nanostructures having remarkable properties^[1]. For the formation of synthetic polymer nanofibers, various important categories of polymers have contributed such as thermoplasts, thermosets, as well as conjugated polymers^[2]. For the formation of polymeric nanocomposites, carbon nanoparticles have been used as essential nano-additives^[3]. Prominently, carbon nanotube, graphene, fullerene, etc. have been reinforced in polymers and studied. In addition to the usually formed films or precipitated polymeric nanocomposites, nanofibers have been designed^[4].

Spinning method is among the most widely focused techniques for polymer nanofibers^[5,6]. Usually, spinning techniques have been found advantageous due to facile controllable process parameters. Spinning techniques have been widely categorized as wet spinning, melt spinning, electrostatic spinning, etc. Solution blow spinning has been initially opted to form desired nanofibers of polymers as well as nanocomposites^[7]. In this technique, varying process parameters have been found to affect the nanofiber diameter and morphology^[8]. Centrifugal jet spinning has also been applied to fabricate micro- or nanofibers^[9,10]. Then, electrohydrodynamic direct writing spinning method has also been adopted to form nanofibers. This method

involves electrical/mechanical forces to form nanofibers^[11,12]. Among spinning techniques, electrospinning has been widely used for the polymer nanofibers. Due to better parameter control to form precisely defined nanofibers, electrospinning technique has accomplished success for high performance polymers and nanocomposite nanofibers^[13]. The resulting electrospun polymers or polymer/carbon nanocomposite nanofibers own superior physiochemical characters^[14]. Consequently, electrospinning technique has been described as a facile, and versatile process to form the nanofibers^[15]. In nanofibrous form, the nanoparticle loading resulted in high-tech physical profiles of these nanostructures materials^[16]. Efficient membranes have been reported using the appropriate nanocomposite design and choice of suitable nanofiber processing techniques^[17]. Electrospinning has been widely studied for the nanocomposite nanofiber formation and the resulting membranes^[18]. In this regard, the electrospinning parameters involved in the nanofibers and membranes formation have been focused. Carbon nanoparticle filled nanocomposite nanofibers have been used to develop high performance nanofibers aiming membrane applications, energy and electronics devices, and biomedical applications^[19].

This review manuscript clarifies basics and potential of electrospinning technique to synthesize the nanocomposite nanofibers and membranes for advanced applications. The electrospun nanocomposite nanofibers covered in this review consist of polymer and carbon nano-additives. In nanofibrous form, the polymer/carbon nanocomposites revealed enhanced physical and methodological features towards membrane application. Superior morphology and properties have been observed due to synergistic effects between matrix-nanofiller in the nanofibers and derived materials. To the best of the knowledge, this overview is novel and ground-breaking to highpoint the area of electrospinning derived nanocomposite nanofibers and membranes. Although, literature research reports have been observed on electrospun nanofibers, however (like our novel comprehensive manuscript) no comprehensive review article has been reported before in this field. Consequently, this article explains recent literature in this area in a reorganized and assembled manner. Hence, this review is novel in terms of the recent literature included, outline and framework, and related discussions. Hence, following this compiled manuscript on nanocomposite nanofibers and membranes will be helpful for the concerned scientists for indispensable future developments towards nanofiber technologies.

2. Nanofillers, nanocomposites, and nanofibers

Carbon nanoparticles have gained research interest in important materials fields^[20]. Few important carbon nanostructures are given in **Figure 1**. Among carbon nano-additives, graphite, carbon nanotube, graphene, fullerene, and countless other forms have been studied^[21,22]. These carbon nanoparticles led to the design of some valuable nanocomposites^[23]. Here, worth mentioning type of the nanocomposites is the polymer and carbon nanocomposites. These materials have been readily prepared through solvent, melt, and in situ techniques^[24]. For the conversion of polymeric nanocomposites to nanofibers, spinning approaches have been applied^[25]. Spinning approaches have definitely improved the dispersion features of the nanoparticles in the nanofibers^[26]. Consequently, enhanced physical performance of the resulting nanocomposites, prepared through facile methods, was observed^[27]. The polymer/carbon nanoparticle nanocomposites have been studied mostly for morphological, thermal, electronic, mechanical, and other profiles^[28].

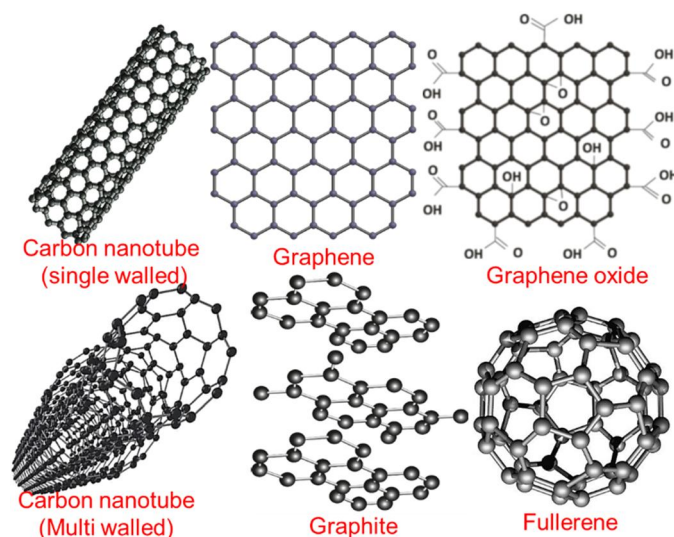


Figure 1. Some carbon nanostructures.

Polymer nanofibers are nanostructures with diameter of few nanometers, whereas length up to millimeters^[29]. These nanofibers may have uniform, wrinkled, hollow, or other forms depending upon the nature of polymer and technique used^[30]. Subsequently, the structural and engineering properties of the nanofibers can be varied^[31]. Innumerable polymers have ability to be processed or formed as nanofibers like epoxies, polyamides, some rubbers, and blends^[32]. The technique used to form these nanofibers have been found considered important^[33]. Spinning methods have been found to be the most effective to develop uniform nanofibers having unique microstructures^[34]. Nanofiber formation technique and related parameters play important role to define the properties of polymer and nanocomposite nanofibrous materials^[35]. The carbon nano-additives have been widely explored to fill the polymer nanofibers^[36]. Due to high surface area and physical properties, the carbon nanoparticle based nanofibers have important technological applications^[37]. In this context, manufacturing strategies have been found important to fabricate the high performance nanofibers^[38].

3. Use of electrospinning technique to form nanofibers

Spinning is the commonly adopted technique reported for the fabrication of polymer nanofibers^[39]. In general, spinning methods can be melt or wet spinning based^[40]. These techniques rely on using an electrostatic spinning mechanism^[41]. Spinning methods have easily controllable parameters for fiber formation^[42]. In this regard, wet spinning method like solution blow spinning has been focused^[43]. Solution blow spinning technique has been designed for spinnable polymer solution. This spinning method has also been adopted for nanocomposites, in addition to polymer nanofibers. The set up of this technique includes a spinning chamber, DC motor, and multiple fiber collector. This technique forms stable polymer solution jet through adjusting parameters like polymer concentration and gas pressure^[44]. The fiber diameter and mat formation depends upon parameter alteration like polymer type and solution concentration. The non-woven micro- and nanofibers have been produced using solution blowing method^[45]. In this method, fiber production rate has been observed high, therefore parameter control has been found complicated, as compared to the electrospinning. Solution blow spinning forms bundled morphology of fiber mats, relative to finely spun electrospun nanofibers and mats. Consequently, electrospinning has been found advantageous, relative to solution blow spinning. **Table 1** shows a comparison of the solution blowing and electrospinning techniques in terms of parameters and nanocomposite used.

Table 1. Comparison on parameters and nanocomposite nanofibers formed using melt blowing and electrospinning.

Parameters or materials	Solution blowing	Electrospinning
Diameter of nanofibers	40 nm to several μm	40 nm to 2 μm
Rate of injection	20 $\mu\text{L}/\text{min}$	5 $\mu\text{L}/\text{min}$
Voltage used	NA.	10–40 kV
Variable parameters	Solution viscosity, nozzle geometry, feeding rate; gas pressure	Viscosity, feeding rate, needle to collector distance; voltage
Use of high polymer concentration	Yes	Fiber property distortion
Commercialization	Yes	Yes
Nanofiber alignment	Yes	Yes
Nanocomposite fiber	Polyaniline/carbon nanoparticle nanofibers; poly(vinyl alcohol)/carbon nanoparticle nanofiber; polystyrene/carbon nanoparticle nanofiber;	Polyamide/carbon nanoparticle nanofiber; polystyrene/carbon nanoparticle nanofiber; polyaniline/carbon nanoparticle nanofibers
Refs.	[46–48]	[49,50]

The electrospinning procedures have been applied for both the wet and melt spinning^[51,52]. The electrospinning technique involves easily controllable parameters for the formation of polymer and nanocomposite nanofibers^[53]. Electrospinning has simple set up consisting of a syringe with needle to hold polymer solution, a pumping structure, a nozzle, a collector, and a power source. Upon the application of applied voltage, polymer or nanocomposite solution is pumped out of the syringe through the needle. Under the electric field effect, the ejected nanofiber elongates and moves towards the collector. Here, polymer and nanofiller types, voltage applied, and pumping speed, etc. affect the nanofiber surface topology and structural and physical properties^[54].

Practically, electrospinning set up has been reported in the horizontal and the perpendicular provisions^[15]. Advanced form of electrospinning is the electrohydrodynamic direct writing mechano-electrospinning method^[55]. In this approach, electrical and mechanical forces have been applied to grow viscous ink and resulting nanofibers^[12]. Hence, the polymer and nanocomposite nanofibers properties have been monitored by varying several parameters of polymer, nanoparticles, as well as the electrospinning set up^[56,57]. **Figure 2** demonstrates a simple demonstration of the electrospinning set up.

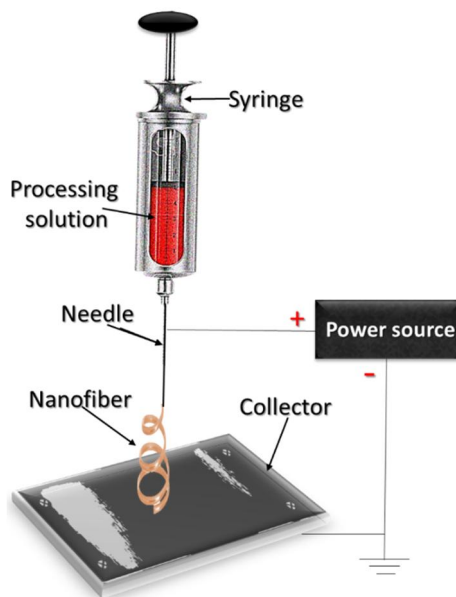


Figure 2. A simple electrospinning set-up.

4. Nanocomposite nanofibers and membranes formed by electrospinning technique

High-tech nanocomposite nanofibers have been designed exhibiting high surface area and physical characteristics^[58]. Carbon nanotube is one dimensional cylindrical nanostructure made up of sp^2 carbons^[59,60]. Carbon nanotube owns unique features and technical potential. Using electrospinning, carbon nanotube has been filled in nanofibers of polymers^[59]. The polyamide and poly(ethylene glycol) thermoplastic matrices have been reinforced with carbon nanotube to form electrospun nanofibers^[61]. In addition, conducting polymer like polyaniline has been filled with carbon nanotube to synthesize the nanofibers^[62].

The polyaniline/carbon nanotube nanofibers have fine nanofiller dispersion, texture, and conductivity properties^[63]. Simotwo et al.^[64] designed the electrospun polyaniline/carbon nanotube nanocomposite nanofibrous membranes as shown in **Figure 3**. Scanning electron microscopy and transmission electron microscopy images reveal fine nanoparticle dispersion in the nanofibers (**Figure 4**). No nanoparticle aggregation was observed due to the spinning and electrostatic forces applied in electrospinning technique. **Figure 5** displays the efficiency of electrospun polyaniline/carbon nanotube nanocomposite nanofibrous membranes for the supercapacitor electrodes. High specific capacitance of 320 F g^{-1} and capacitance retention of 83% were observed for nanocomposite nanofibers. Superior supercapacitor performance was attributed to graphene dispersion and formation of conductive network in the polymer matrix.

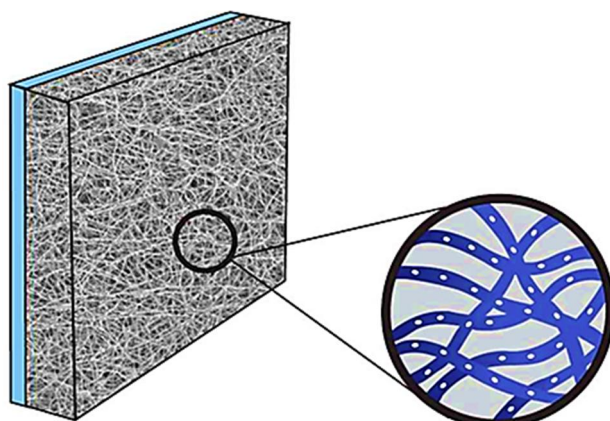


Figure 3. Polyaniline/carbon nanotube nanocomposite nanofibrous membranes^[64]. Reproduced with permission from ACS.

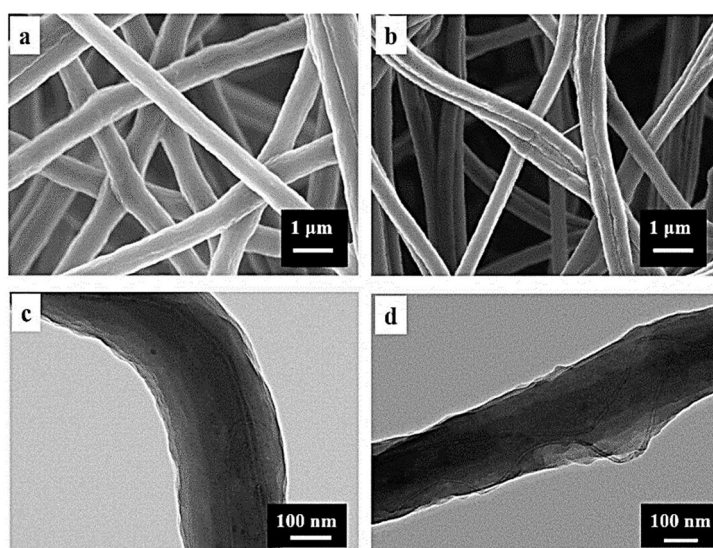


Figure 4. Scanning electron microscopy images of (a) polyaniline and (b) polyaniline/carbon nanotube electrospun nanofibers with an average nanofiber diameter of $678 \pm 54 \text{ nm}$ and $491 \pm 86 \text{ nm}$, respectively; (c and d) Transmission electron microscopy images of polyaniline/carbon nanotube nanofiber showing distribution of nanotube^[64]. Reproduced with permission from ACS.

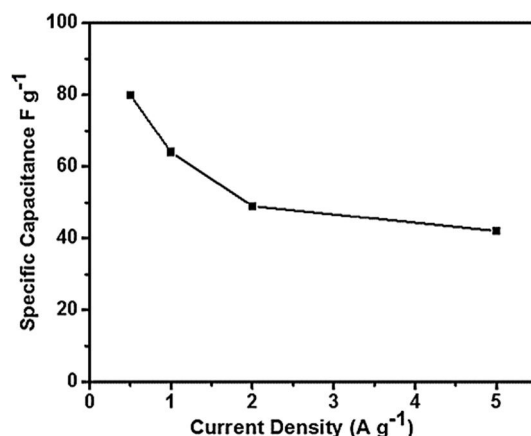


Figure 5. Plots showing electrochemical performance of symmetric polyaniline/carbon nanotube for specific capacitance as a function of charge-discharge rates^[64]. Reproduced with permission from ACS.

Graphene is a two dimensional nanosheet of sp^2 hybrid carbon atoms^[65,66]. Owing to advantageous physical characteristics, graphene has been employed to manufacture high performance nanomaterials^[67]. Among polymer matrices, nylons or polyamides have been explored for nanocomposite nanofibers^[68,69]. Accordingly, the graphene oxide reinforced nylon 6 and nylon 6,6 were processed for nanocomposite nanofibers through electrospinning^[70,71]. The nanofibers reveal small diameters in the range of 100–200 nm. Moreover, the nanofiller loading up to 10 wt.% depicted fine dispersion in nanocomposite nanofibers. Leyva-Porras et al.^[72] fabricated the electrospun nanofibers of nylon 6/nitroxide-functional graphene oxide. Nitroxide-functionalized graphene oxide was formed with oxoammonium salt through the reaction between the aromatic alcohol protons and graphene oxide acid moieties (**Figure 6**). Scanning transmission electron microscopy images of modified graphene oxide and nanocomposite nanofibers are displayed in **Figure 7**. In the micrographs, the finely dispersed functional graphene oxide can be seen in the nanofibers owing to matrix nanofiller intersections. Effectiveness of electrospinning technique was responsible to form homogeneous electrospun nanofibers.

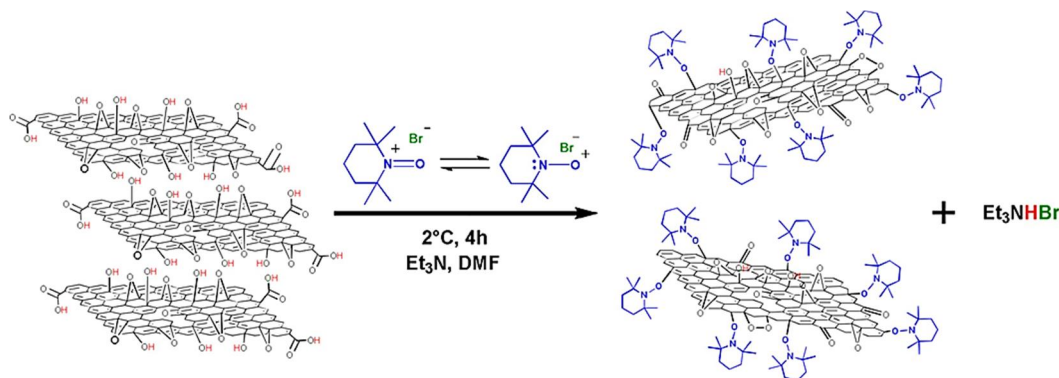


Figure 6. Exfoliation and functionalization of graphene oxide with nitroxide moieties using oxoammonium salts^[72]. Et₃N = triethyl amine; DMF = dimethyl formamide. Reproduced with permission from Elsevier (Open access, PMC Copyright).

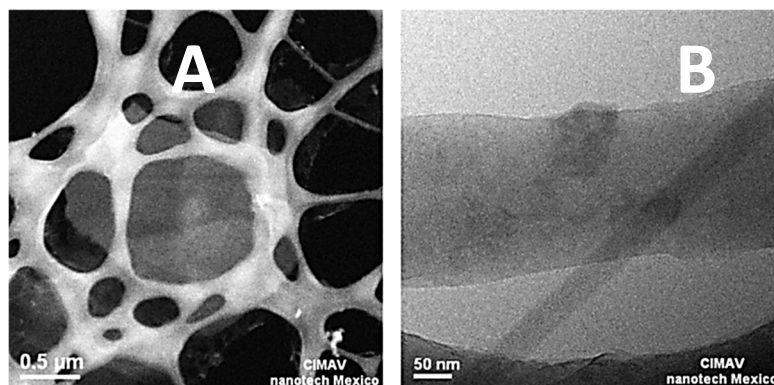


Figure 7. STEM images showing (A) few layers of GOFT platelet (less than 4); and (B) nanocomposite nanofiber containing a thicker GO platelet^[72]. STEM = Scanning transmission electron microscopy; GOFT = nitroxide-functionalized graphene oxide layers; GO = graphene oxide. Reproduced with permission from Elsevier (Open access, PMC Copyright).

Xu and Gao^[73] fabricated the nylon and graphene filled nanocomposites using an in situ technique. The caprolactam monomer was polymerized in the presence of graphene oxide nanosheets to form the nanomaterials. Graphene oxide was filled in varying amounts of 0.1–10 wt.%. Then, during in situ polymerization, graphene oxide was converted to graphene and grafted to polymerized nylon matrix. **Figure 8** expresses the route for the in situ formation of graphene and grafting to polymerized nylon 6. During in situ process, consistent graphene nanosheet dispersion was observed. **Figure 9** displays the scanning electron microscopy images of the nylon/graphene nanocomposites. At low and high resolutions, fine graphene dispersion can be observed in the matrix due to in situ process. **Figure 10** illustrates the electrospun nanofiber formation of the nylon/graphene nanomaterials. Including 0.01 wt.% graphene contents resulted in higher tensile strength of 123 MPa and Young's modulus of 722 MPa, relative to neat nylon 6 nanofibers (50% lower values of properties). The property enhancement was attributed to graphene dispersion and covalent grafting to the polyamide matrix^[74].

Another important matrix for electrospun nanofiber is poly(vinyl alcohol) with graphene additive^[75,76]. The electrical conductivity, optical, and thermal stability features of the poly(vinyl alcohol) nanofibers have been found to enhance with graphene loadings^[77].

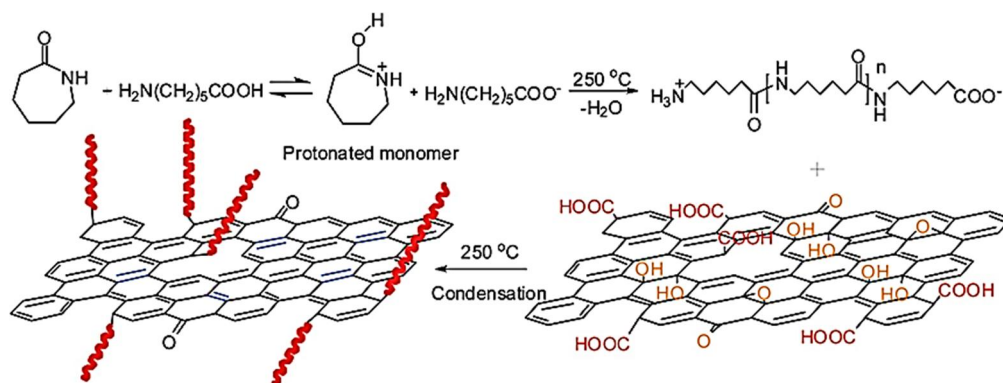


Figure 8. Synthesis of nylon/graphene nanocomposites formed using in situ ring opening polymerization of caprolactam^[73]. Reproduced with permission from ACS.

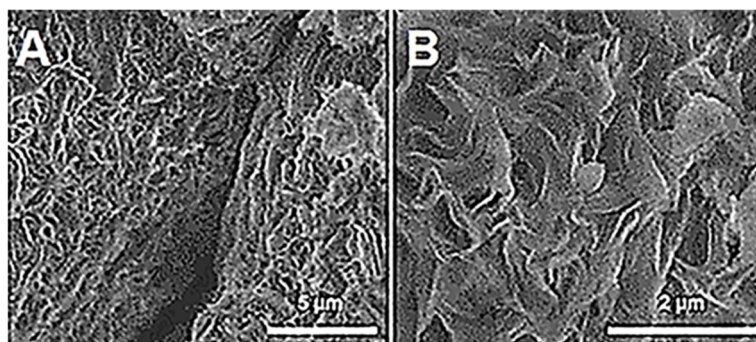


Figure 9. Scanning electron microscopy images of 0.5 wt.% graphene grafted nylon nanocomposite, at low and high resolution respectively^[73]. Reproduced with permission from ACS. Reproduced with permission from ACS.

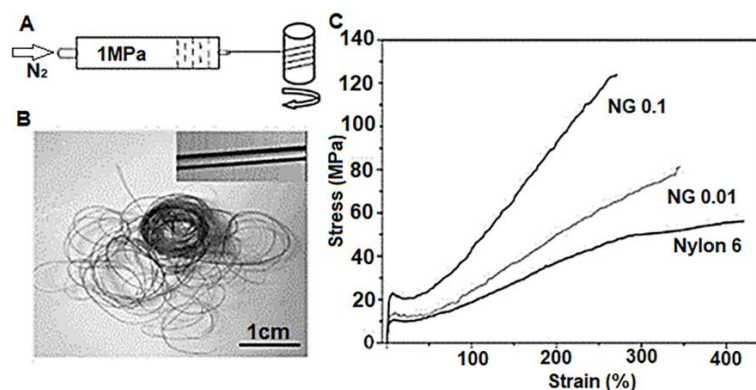


Figure 10. (A) Apparatus of melt spinning of nylon graphene (NG) nanocomposites nanofibers at 250 °C; and (B) Photograph of 0.5 wt.% nanofibers, optical micrograph with nanofiber diameter 50 μm (inset); and (C) Stress-strain curves of neat polyamide 6 and nanocomposite nanofibers with 0.01 and 0.1. wt.% graphene contents^[73]. Reproduced with permission from ACS.

In addition to carbon nanoparticles, metal nanoparticles have also been filled in the nanofibers^[78]. Some important designs of metal and inorganic nanoparticles based electrospun nanofibers include transition metal like Fe, Co, Ni based nanofibers, Mg and Yb doped In_2O_3 nanofibers, and $\text{CoNiSe}_2@\text{N}$ -carbon nanofibers^[79,80]. The resulting high performance inorganic nanoparticle filled nanofibers have been employed for electrocatalysts and energy related devices and systems^[81]. **Table 2** presents an outline of the specifications of various carbon nanoparticle nanocomposite nanofibers formed by electrospinning technique.

Table 2. Specifications of carbon nanoparticle nanocomposite nanofibers.

Polymer nanocomposite	Diameter/Size	Solvent/Concentration	Physical properties	Ref.
Polyaniline/carbon nanotube nanofibrous membranes	Average nanofiber diameter 491 ± 86 nm	Polyethylene oxide solution	Specific capacitance 320 F g^{-1} ; capacitance retention 83%	[64]
Nylon 6/nitroxide-functional graphene oxide	165–190 nm	Dimethyl formamide	Physical interactions; Well dispersed microstructure	[72]
Nylon/graphene	Diameter 50 μm	Melt	Tensile strength 123 MPa; Young's modulus 722 MPa	[73]
Polyamide/graphene	76–338 nm	Hexafluoroisopropanol; 0.005–0.01 wt.%	Increase in tensile strength, Young's modulus fracture, toughness by 56%, 113%, and 250%, respectively	[82]
Polyaniline/poly (methyl methacrylate)/amino-functionalized graphene	35–133 nm	Dimethyl formamide	Thermal stability	[83]
Poly(ϵ -caprolactone)/graphene oxide	201–264 nm	Glacial acetic acid; 1.5 w/v%	Tensile stress increase by 189%	[84]
Poly(ϵ -caprolactone)/graphene	121–154 nm	Dichloromethane/methanol; 10–12 wt.%	Young's modulus tensile strength of 3771 MPa and 56.08 MPa, respectively	[85]
Poly(ϵ -caprolactone)/reduced graphene oxide	100–130 nm	Glacial acetic acid; 1.5 w/v%	Tensile strength increases by 304%	[86]

5. Applications of nanocomposite nanofibers and membranes prepared by electrospinning technique

Electrospinning method involves electrostatic spinning of material to form fibers. It has been adopted as an effective technique to form nanofibers having diameter in nanometer range under the influence of electric field. Including carbon nanoparticles in nanofibers have numerous advantages, relative to pristine polymer nanofibers. Particularly, the production of carbon nanoparticle filled electrospun nanofibers resulted in high surface area, homogeneous surface, topography, precise porosity, variable diameter/shapes, and specific designs/functions, which have not been detected for unfilled polymer nanofibers or membranes (**Figure 11**).

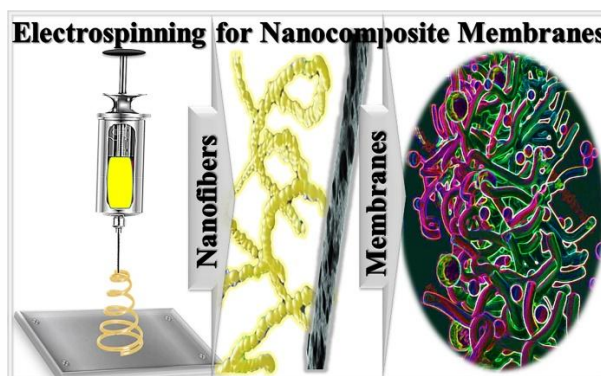


Figure 11. Electrospun nanofibers for nanocomposite membranes.

In addition, nanoparticle filled nanofibers own better functionalization tendencies, fine percolation pathways for electrical conductivity and superior mechanical properties than polymer fibers^[87]. Electrospinning technique has been used to alter the specifications of nanofibers according to the specific desired applications. Mainly the fiber parameters such as surface area to volume ratio, diameter, length, surface properties, porosity, morphology, etc. have been controlled by adjusting the electrospinning parameters such as solution/melt viscosity, flow rate, spinning speed, spinning mode, voltage applied distance between needle and collector^[88]. Applications of electrospinning technique have been found in the fields of filtration, energy sector, textile, biomedical, etc. In filtration processes, electrospinning method has been used to form nanofibers of high surface/volume ratio and controlled porosity for crucial environmental applications like air filtration and water purification^[89]. By appropriately controlling the electrospinning parameters, molecular permeability and selectivity can be managed for the filtration of hazardous particulate matter. For textile application, electrospinning has been used to form nanofibers and membranes of very small size, high surface area, and appropriate porosity^[90]. The fiber chemistry has been found essential to choose nanofibers for textile purposes. Development of strategies for fine quality regulation of the electrospinning process may form high quality textile nanofibers and membranes for commercialization. Biomedical applications require the use of electrospinning technique to form nanofibers maintaining the morphology, strength, biocompatibility, degradation rate, drug release profile, and interactions with living cells for drug delivery as well as tissue engineering purposes^[91]. Then, wide ranging applications have been observed for the energy sector. In energy sector, electrospinning technique has offered high aspect ratio, robustness, and effective electron or charge transportation of the electrospun nanofibers and membranes^[89,92]. Consequently, the fields of energy storage and production like supercapacitors, Li ion batteries, and solar cells have been focused. Electrospinning has been used to create appropriate defects and surface area to support the charge passage and interfacial effects. By controlling the electrospinning parameters, efficient electrodes have been developed to overcome the challenges in current supercapacitor technology^[93]. For Li-ion batteries, the electrode must be designed with precise electrospinning parameters to attain high capacity, fast charging rates, and long cycle life^[94]. Electrospinning technique has also been found competent for designing nanofibers for dye-sensitized solar

cells for high efficiency^[95]. Some significant designs of inorganic or metal-organic hybrid based electrospinning nanofibers have been applied for high performance gas sensing and chemiresistive sensing devices^[96,97]. This technique offers an efficient way to form ultra-fine nanofibers and nanocomposite meshes for superior gas sensing performance.

For polymer/carbon nanocomposite nanofibers, energy storage applications related to supercapacitors have been reported^[98]. Including carbon nanoparticles can yield efficient supercapacitor electrodes having high surface area, capacitance, electron conduction, and structural properties^[99]. Zhou et al.^[100] reported on polyaniline and graphene nanocomposite nanofibers developed through electrospinning technique. The electrospun nanofibers have been used for supercapacitor electrodes^[101]. The potential polyaniline/graphene electrode had higher specific capacitance (250 Fg^{-1}) than that of unfilled polyaniline (175 Fg^{-1}) electrode. Electrospinning was found efficient to form the nanofibers having high conductivity and capacitance properties. Significantly, the electrospun nanocomposite nanofibers have been used to form the photovoltaics^[102]. Photovoltaic systems based on polythiophene and fullerene derivatives have been reported^[103]. These devices have high power conversion efficiency of $>5\%$ ^[104]. Kurniawan et al.^[105] established poly(3-hexylthiophene):phenyl- C_{61} -butyric acid methyl ester nanofibers for photovoltaics. As prepared nanofibers were used after thermally annealed. **Table 3** shows the photovoltaic characters of the nanofibers. The thermally annealed nanofibers at $150 \text{ }^\circ\text{C}$ (30 min) had significantly higher power conversion efficiency, short circuit current density, and fill factor, relative to non-annealed nanofibers. **Figure 12** also depicts the I-V features of electrospun nanofibers based photovoltaics. Better results for thermally annealed nanofibers were observed due to synergistic effect in nanostructure developed after heating. Moreover, the polymer nanofibers have wide scope for biomedical relevance. The electrospun nanocomposite nanofibers have also been used in this field. For tissue engineering scaffolds, poly(vinyl alcohol) and graphene based nanofibers have been prepared by electrospinning method^[106].

Table 3. Photovoltaic properties of the nanofibers^[105]. PCE = power conversion efficiency; J_{sc} = short circuit current density; FF = fill factor; P3HT:PCBM = poly(3-hexylthiophene):phenyl- C_{61} -butyric acid methyl ester; P3HT-NF:PCBM = poly(3-hexylthiophene)-nanofiber:phenyl- C_{61} -butyric acid methyl ester; NA = non-annealed; TA= thermally annealed. Reproduced with permission from ACS.

Sample	PCE (%)	J_{sc} (mA/cm^2)	FF
P3HT:PCBM (NA)	1.08	4.56	0.33
P3HT:PCBM (TA)	3.57	8.57	0.66
P3HT-NF:PCBM	2.40	8.21	0.50

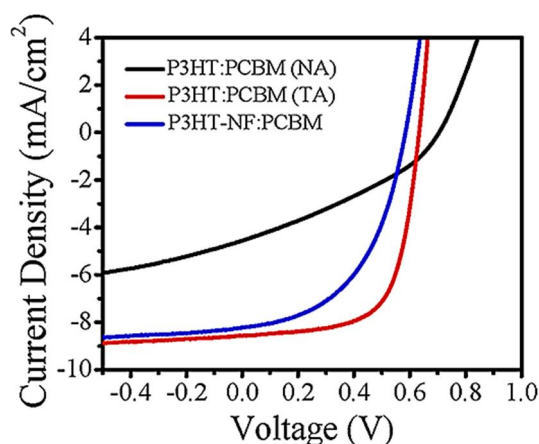


Figure 12. I-V characteristics of photovoltaic devices fabricated with neat, thermally annealed P3HT:PCBM, and P3HT-NF:PCBM materials^[105]. P3HT:PCBM = poly(3-hexylthiophene): phenyl- C_{61} -butyric acid methyl ester; P3HT-NF:PCBM = poly(3-hexylthiophene)-nanofiber:phenyl- C_{61} -butyric acid methyl ester; NA = non-annealed; TA= thermally annealed. Reproduced with permission from ACS.

Mostly, polymer fibers have been researched for wide ranging applications related to membranes, coatings, packages, weaves, tissue engineering, and other arenas^[107]. Here, the carbon nanoparticle filled nanofibers have high-tech engineering applications^[108,109]. The perfectly engineered nanofiber based membranes have been used for separation and purification applications^[110]. These electrospun nanofibrous membranes have technical potential for water remediation applications^[111]. The topography, permeability, selectivity, porosity, robustness, and other membrane properties have been studied^[112]. The nanofiller dispersion and alignment in nanofibers and fiber orientation in membranes define the final membrane potential. Electrospun polymer/carbon nanocomposite membranes for nanofiltration, ultrafiltration, distillation, and osmosis have been designed^[113]. The electrospun membranes have been observed for the high flux, permeability, and rejection rates, relative to traditional membranes^[114]. These innovative membranes have low weight, low price, optimum porosity, and large scale processing characters. Hence, electrospinning has been referred as an emergent multipurpose practice to form high performance filtration membrane systems.

6. Conclusions

Key points of this review article include: (i) understanding the fundamentals of nanofillers, nanocomposites, and nanofibers; (ii) basics and use of electrospinning technique to synthesize nanofibers; (iii) effect of electrospinning technique to fabricate the nanocomposite based nanofibers and membranes; and (iv) important applications of electrospun nanocomposite nanofibers and membranes. Performance of electrospun nanocomposite nanofibers and membranes depends upon the factors like nanoparticle dispersion in the nanofibers, matrix-nanofiller interactions like electrostatic, hydrogen bonding, and covalent interactions, and the adjustment of parameters of electrospinning technique. Concisely, the review article explains the design of nanofibers focusing the electrospinning technique. This practice owns facile and efficient set up and easily controllable parameters to develop fine and advanced nanofibers. Development of nanofibers and nanocomposite nanofibers through electrospinning has been found remarkable to unfold fine microstructure, physical properties, and technical utilizations in energy devices to membranes. The nanocomposites, particularly, the carbon filled nanofibers have been found technically efficient due to facile manufacturing parameters applied to controlling the final designs. Further research in this field may lead to novel nanofiber design by overcoming the challenges related to nanoparticle dispersion, material compatibility, and parameter control.

Initially in this article, fundamentals of nanofillers, nanocomposites, and nanofibers have been stated to give reader a quick knowledge of these nanomaterials. Afterwards, common spinning technique like solution blow spinning has been discussed in addition to electrospinning method to reveal the specifications, advantages, and differences of electrospinning techniques with respect to traditional spinning methods to form high performance nanofibers. Consequently, major state-of-the-art of electrospun nanocomposite nanofibers and membranes have been discussed in subsequent section. Numerous carbon nanoparticle filled nanofiber designs have been discussed with advantages of including carbon nanoparticles in nanofibers and property benefits compared with the pristine polymer nanofibers. For numerous polymer nanocomposite nanofiber, diameter, solvent used, processing conditions, and physical properties have been discussed. Using this technique solution as well as melt samples have been successfully processed. The electrospun nanocomposite nanofibers have uniform nanoparticle dispersion and surface to enhance the physical properties like mechanical, thermal, conductivity, and other features. Here, choice of polymer, solution concentration, electrospinning speed, solution flow rate, applied voltage, etc. affect the final characters such as consistency, surface, morphology, and diameter of the nanocomposite nanofibers. Then, a detailed section presents the application areas of the electrospun nanofibers in supercapacitors, solar cells, and other probabilities have been discussed. Due to better dispersion and conductivity properties, device applications have been preferred for electrospun carbon nanoparticle nanocomposite designs. However, engineered nanofiber membranes have been suggested for

future separation or purification utilizations on industrial level. In addition, the future scope of these nanofibers and membranes can be seen in the field of drug transfusion and tissue engineering. Future developments in the field of polymer/carbon nanoparticle nanocomposite based nanofibers and membranes have been found associated to novel designs and advanced electrospinning practices applied.

Conflict of interest

The authors declare no conflict of interest.

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