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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 nan-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].

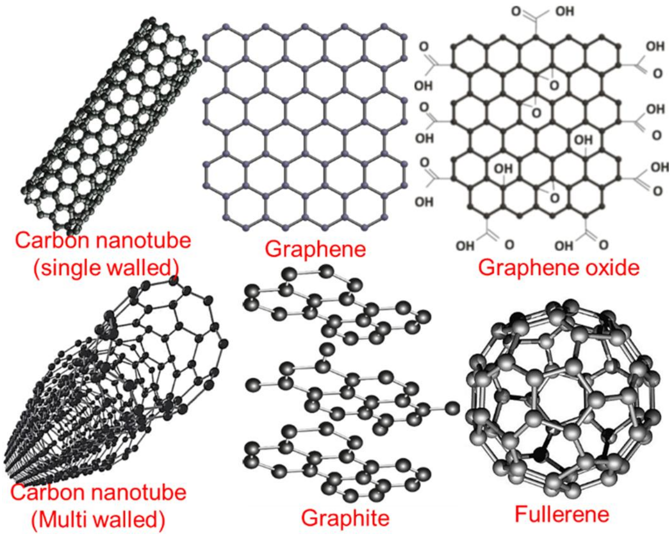

Figure 1. Some carbon nanostructures.

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 µL/min	5 µL/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 held 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.

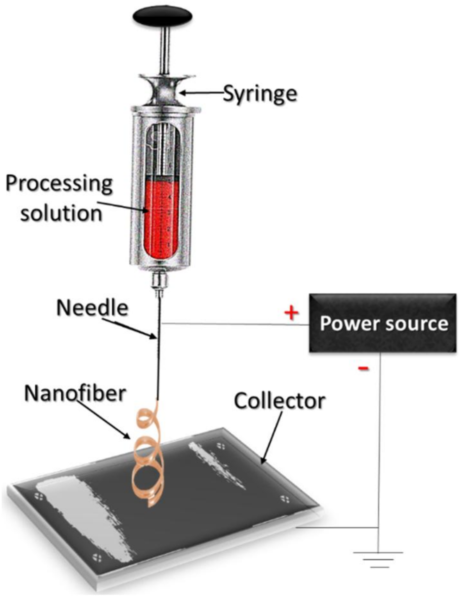

Figure 2. A simple electrospinning set-up.

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.

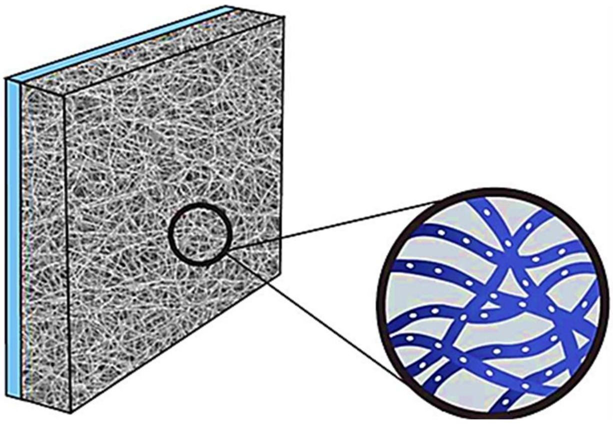

Figure 3. Polyaniline/carbon nanotube nanocomposite nanofibrous membranes[64]. Reproduced with permission from ACS.

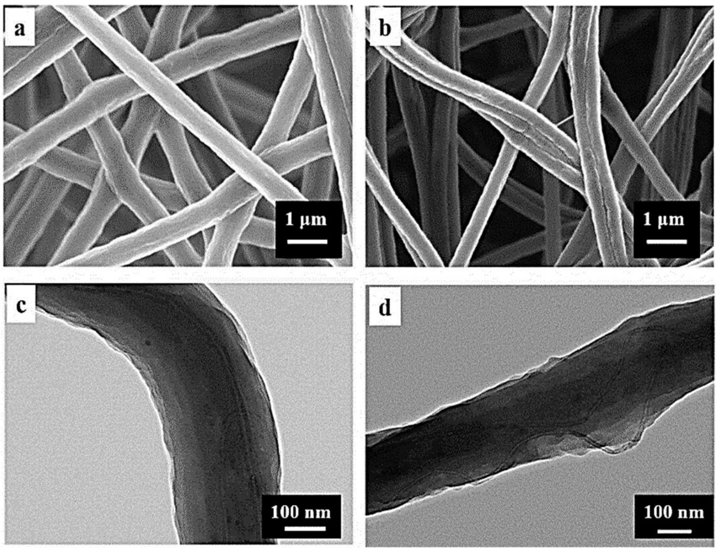

Figure 4. Scanning electron microscopy images of **(a)** polyaniline and **(b)** polyaniline/carbon nanotube electrospun nanofibers with an average nanofiber diameter of 678 ± 54 nm and 491 ± 86 nm, respectively; **(c** and **d)** Transmission electron microscopy images of polyaniline/carbon nanotube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

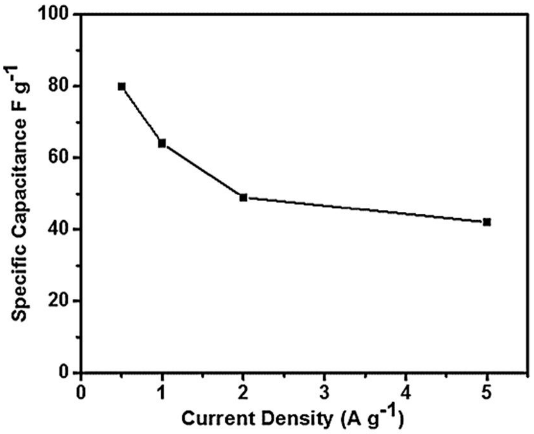

Figure 5. Plots showing electrochemical performance of symmetric polyaniline/carbon nanotube for specific capacitance as a function of charge-discharge rates[64]. Reproduced with permission from ACS.

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.

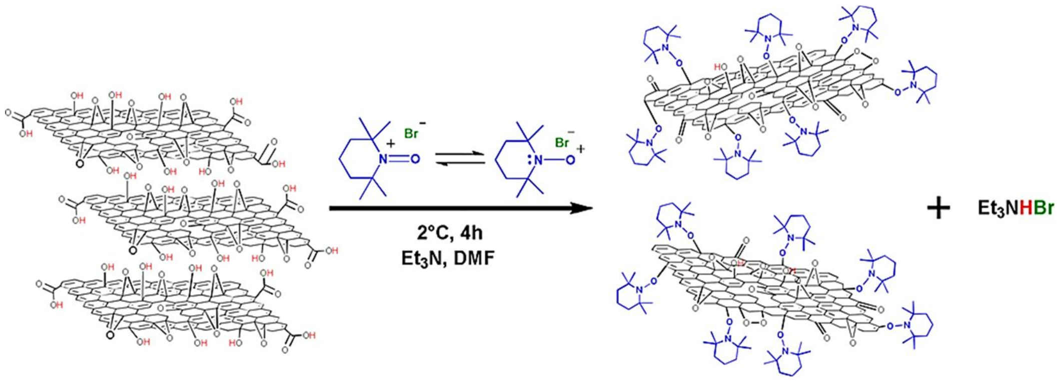

Figure 6. Exfoliation and functionalization of graphene oxide with nitroxide moieties using oxoammonium salts[72]. Et_3N = triethyl amine; DMF = dimethyl formamide. Reproduced with permission from Elsevier (Open access, PMC Copyright).

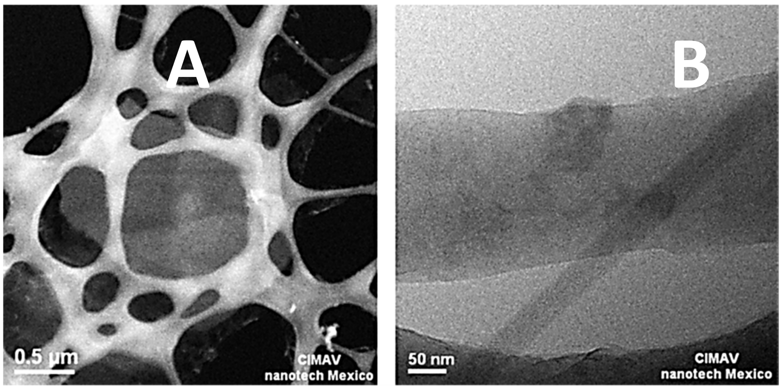

Figure 7. STEM images showing (A) few layers of GOFT platelet (less than 4); and (B) nanocomposite nanofiber containing a thicker GO platelet[72]. STEM = Scanning transmission electron microscopy; GOFT = nitroxide-functionalized graphene oxide layers; GO = graphene oxide. Reproduced with permission from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

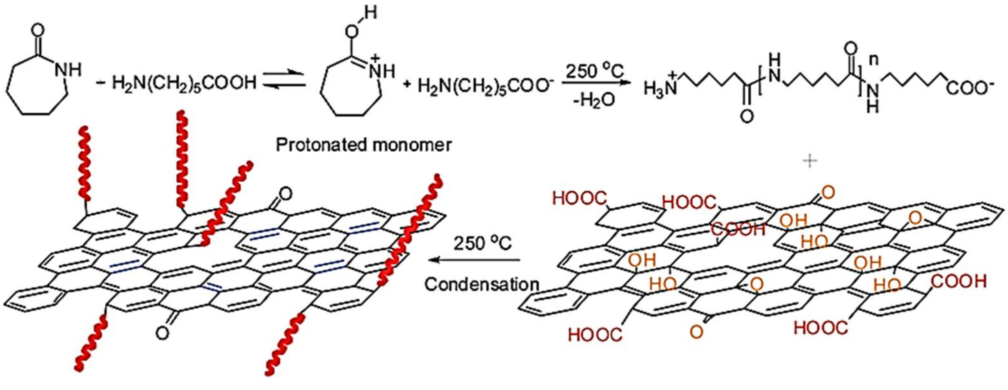

Figure 8. Synthesis of nylon/graphene nanocomposites formed using in situ ring opening polymerization of caprolactam[73]. Reproduced with permission from ACS.

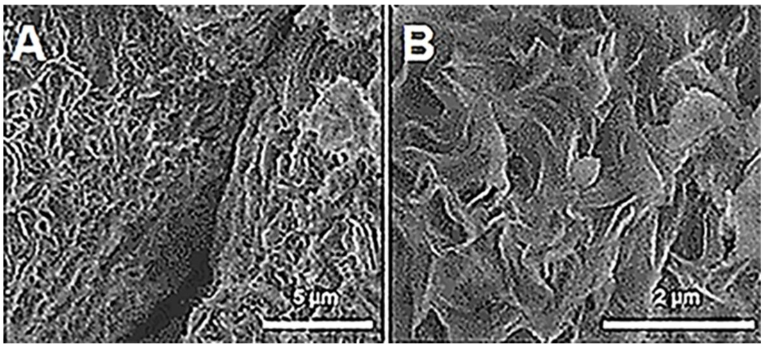

Figure 9. Scanning electron microscopy images of 0.5 wt.% graphene grafted nylon nanocomposite, at low and high resolution respectively[73]. Reproduced with permission from ACS. Reproduced with permission from ACS.

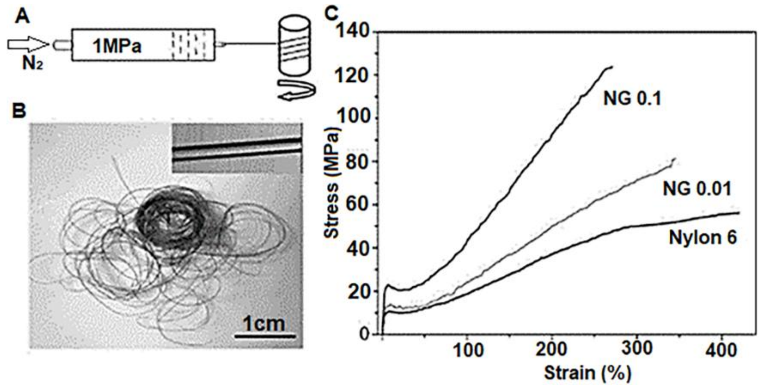

Figure 10. (A) Apparatus of melt spinning of nylon graphene (NG) nanocomposites nanofibers at 250 °C; and **(B)** Photograph of 0.5 wt.% nanofibers, optical micrograph with nanofiber diameter 50 µm (inset); and **(C)** Stress-strain curves of neat polyamide 6 and nanocomposite nanofibers with 0.01 and 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 $CoNiSe_2$@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**).

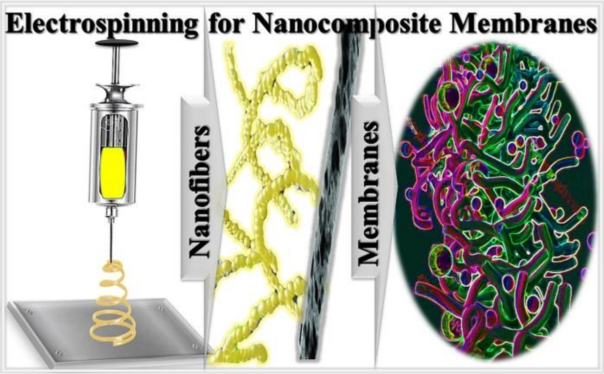

Figure 11. Electrospun nanofibers for nanocomposite membranes.

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 manages 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 bee 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 deliver 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 °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/cm²)	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

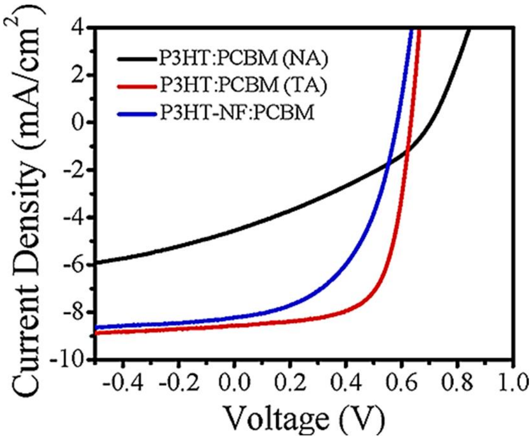

Figure 12. I-V characteristics of photovoltaic devices fabricated with neat, thermally annealed P3HT:PCBM, and P3HT-NF:PCBM materials[105]. P3HT:PCBM = poly(3-hexylthiophene): phenyl-C_{61}-butyric acid methyl ester; P3HT-NF:PCBM = poly(3-hexylthiophene)-nanofiber:phenyl-C_{61}-butyric acid methyl ester;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

References

1. Huang X, Chen Y. Surface grafting of cellulose triacetate hollow fiber membranes with Ag@ZnO-hyperbranched polyglycerols nanoparticles for constructing antifouling and antibacterial surfaces. *Characterization and Application of Nanomaterials* 2023; 6(1). doi: 10.24294/can.v6i1.2538
2. Wang JJ, Shen ZH, Zhou WY, et al. Mesoscale computational prediction of lightweight, thermally conductive polymer nanocomposites containing graphene-wrapped hollow particle fillers. *Characterization and Application of Nanomaterials* 2021; 4(1): 40. doi: 10.24294/can.v4i1.1292
3. Kausar A, Ahmad I, Lam TD. High-tech graphene oxide reinforced conducting matrix nanocomposites—Current status and progress. *Characterization and Application of Nanomaterials* 2023; 6(1). doi: 10.24294/can.v6i1.2637
4. Pathak AK, Yokozeki T. Recycled Carbon nanofiber-polypropylene nanocomposite: A step towards sustainable structural material development. *Journal of Composites Science* 2022; 6(11): 332. doi: 10.3390/jcs6110332
5. Ganguly S. Preparation/processing of polymer-graphene composites by different techniques. In: *Polymer Nanocomposites Containing Graphene*. Elsevier; 2022. pp. 45–74. doi: 10.1016/b978-0-12-821639-2.00015-x
6. Nemati S, Kim S, Shin YM, et al. Current progress in application of polymeric nanofibers to tissue engineering. *Nano Convergence* 2019; 6(1). doi: 10.1186/s40580-019-0209-y
7. Liu R, Xu X, Zhuang X, et al. Solution blowing of chitosan/PVA hydrogel nanofiber mats. *Carbohydrate Polymers* 2014; 101: 1116–1121. doi: 10.1016/j.carbpol.2013.10.056
8. Oliveira JE, Mattoso LHC, Orts WJ, et al. Structural and morphological characterization of micro and nanofibers produced by electrospinning and solution blow spinning: A comparative study. *Advances in Materials Science and Engineering* 2013; 2013: 1–14. doi: 10.1155/2013/409572
9. Marjuban SMH, Rahman M, Duza SS, et al. Recent advances in centrifugal spinning and their applications in tissue engineering. *Polymers* 2023; 15(5): 1253. doi: 10.3390/polym15051253
10. Madhi Alsharif A. Power law liquid jets' trajectories and instability during centrifugal spinning. *Alexandria Engineering Journal* 2023; 68: 301–314. doi: 10.1016/j.aej.2023.01.036
11. Duan Y, Ding Y, Xu Z, et al. Helix electrohydrodynamic printing of highly aligned serpentine micro/nanofibers. *Polymers* 2017; 9(12): 434. doi: 10.3390/polym9090434
12. Zhang Z, He H, Fu W, et al. Electro-hydrodynamic direct-writing technology toward patterned ultra-thin fibers: Advances, materials and applications. *Nano Today* 2020; 35: 100942. doi: 10.1016/j.nantod.2020.100942
13. Mahmoudi N, Simchi A. On the biological performance of graphene oxide-modified chitosan/polyvinyl pyrrolidone nanocomposite membranes: In vitro and in vivo effects of graphene oxide. *Materials Science and Engineering: C* 2017; 70: 121–131. doi: 10.1016/j.msec.2016.08.063
14. Luraghi A, Peri F, Moroni L. Electrospinning for drug delivery applications: A review. *Journal of Controlled Release* 2021; 334: 463–484. doi: 10.1016/j.jconrel.2021.03.033
15. Yadav TC, Srivastava AK, Mishra P, et al. *Electrospinning: An Efficient Biopolymer-Based Micro- and Nanofibers Fabrication Technique. Next Generation Biomanufacturing Technologies*. ACS Publications; 2019. pp. 209–241. doi: 10.1021/bk-2019-1329.ch010
16. Zheng Q, Cao WQ, Zhai H, et al. Tailoring carbon-based nanofiber microstructures for electromagnetic absorption, shielding, and devices. *Materials Chemistry Frontiers* 2023; 7(9): 1737–1759. doi: 10.1039/d2qm01271e
17. Xu H, Yagi S, Ashour S, et al. A review on current nanofiber technologies: Electrospinning, centrifugal spinning, and electro-centrifugal spinning. *Macromolecular Materials and Engineering* 2022; 308(3). doi: 10.1002/mame.202200502
18. Al-Dhahebi AM, Ling J, Krishnan SG, et al. Electrospinning research and products: The road and the way forward. *Applied Physics Reviews* 2022; 9(1). doi: 10.1063/5.0077959
19. Bora P, Bhuyan C, Borah AR, et al. Carbon nanomaterials for designing next-generation membranes and their emerging applications. *Chemical Communications* 2023; 59(76): 11320–11336. doi: 10.1039/d3cc03490a
20. Kumar V, Alam MN, Manikkavel A, et al. Silicone rubber composites reinforced by carbon nanofillers and their hybrids for various applications: A review. *Polymers* 2021; 13(14): 2322. doi: 10.3390/polym13142322

21. Alatawna A, Birenboim M, Nadiv R, et al. The effect of compatibility and dimensionality of carbon nanofillers on cement composites. *Construction and Building Materials* 2020; 232: 117141. doi: 10.1016/j.conbuildmat.2019.117141
22. Kausar A. Nanocarbon in polymeric nanocomposite hydrogel—Design and multi-functional tendencies. *Polymer-Plastics Technology and Materials* 2020; 59(14): 1505–1521. doi: 10.1080/25740881.2020.1757106
23. Mas B, Fernández-Blázquez JP, Duval J, et al. Thermoset curing through Joule heating of nanocarbons for composite manufacture, repair and soldering. *Carbon* 2013; 63: 523–529. doi: 10.1016/j.carbon.2013.07.029
24. Choudhary V, Gupt A. Polymer/carbon nanotube nanocomposites. *Carbon Nanotubes - Polymer Nanocomposites* 2011. doi: 10.5772/18423
25. Chu CC, White KL, Liu P, et al. Electrical conductivity and thermal stability of polypropylene containing well-dispersed multi-walled carbon nanotubes disentangled with exfoliated nanoplatelets. *Carbon* 2012; 50(12): 4711–4721. doi: 10.1016/j.carbon.2012.05.063
26. Al-Osaimi J, Alhosiny N, Badawi A, Abdallah S. The effects of CNTs types on the structural and electrical properties of CNTs/PMMA nanocomposite films. *International Journal of Engineering & Technology* 2013; 13: 77–79.
27. Khan NI, Halder S, Das S, et al. Graphitic nanoparticles functionalized with epoxy moiety for enhancing the mechanical performance of hybrid carbon fiber reinforced polymer laminated composites. *Polymer Composites* 2020; 42(2): 678–692. doi: 10.1002/pc.25857
28. Latif Z, Ali M, Lee EJ, et al. Thermal and mechanical properties of nano-carbon-reinforced polymeric nanocomposites: A review. *Journal of Composites Science* 2023; 7(10): 441. doi: 10.3390/jcs7100441
29. Maliszewska I, Czapka T. Electrospun polymer nanofibers with antimicrobial activity. *Polymers* 2022; 14(9): 1661. doi: 10.3390/polym14091661
30. Al-Abduljabbar A, Farooq I. Electrospun polymer nanofibers: Processing, properties, and applications. *Polymers* 2022; 15(1): 65. doi: 10.3390/polym15010065
31. Peng K, Huang H. Investigating the origin of the core-shell structure of polymeric nanofibers during fabrication process at the atomistic scale. *Applied Surface Science* 2023; 608: 155105. doi: 10.1016/j.apsusc.2022.155105
32. Dou L, Yang B, Lan S, et al. High-entropy-nanofibers enhanced polymer nanocomposites for high-performance energy storage. *Advanced Energy Materials* 2023; 13(11). doi: 10.1002/aenm.202203925
33. Zhao G, Shi L, Yang G, et al. 3D fibrous aerogels from 1D polymer nanofibers for energy and environmental applications. *Journal of Materials Chemistry A* 2023; 11(2): 512–547. doi: 10.1039/d2ta05984c
34. Wortmann M, Westphal M, Kaltschmidt B, et al. Nanofibers are a matter of perspective: Effects of methodology and subjectivity on diameter measurements. *Nanoscale Advances* 2023; 5(21): 5900–5906. doi: 10.1039/d3na00528c
35. Sharma A, Kokil GR, He Y, et al. Inorganic/organic combination: Inorganic particles/polymer composites for tissue engineering applications. *Bioactive Materials* 2023; 24: 535–550. doi: 10.1016/j.bioactmat.2023.01.003
36. Zhang Y, Zhu B, Cai X, et al. Uniform doping of onion-like carbon nanofillers in carbon nanofibers via functionalization and in-situ polymerization for improved fiber graphitic structure and mechanical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2023; 674: 131874. doi: 10.1016/j.colsurfa.2023.131874
37. Sacco LN, Vollebregt S. Overview of engineering carbon nanomaterials such as carbon nanotubes (CNTs), carbon nanofibers (CNFs), graphene and nanodiamonds and other carbon allotropes inside porous anodic alumina (PAA) templates. *Nanomaterials* 2023; 13(2): 260. doi: 10.3390/nano13020260
38. Kausar A. State-of-the-art of fullerene-based nanocomposite nanofibers—Enterprise and technological amenabilities. *Polymer-Plastics Technology and Materials* 2023; 62(9): 1157–1177. doi: 10.1080/25740881.2023.2204923
39. Gobiraman A, Santhosh N, Vishvanathperumal S. *Biodegradable Polymeric Nanofibers Prepared via Electrospinning. Electrospun Nanofibres*. CRC Press; 2023. pp. 167–190. doi: 10.1201/9781003333814-9
40. Huang T, Marshall LR, Armantrout JE, et al. Production of Nanofibers by Melt Spinning. U.S. Patent 8,277,711, 2 October 2012.
41. Ye P, Guo Q, Zhang Z, et al. High-speed centrifugal spinning polymer slip mechanism and PEO/PVA composite fiber preparation. *Nanomaterials* 2023; 13(7): 1277. doi: 10.3390/nano13071277
42. Rajendaren V, Saufi SM, Zahari MAKM. Effect of spinning parameter on the properties and performance of hollow fiber supported liquid membrane for levulinic acid extraction. *Korean Journal of Chemical Engineering* 2023; 40(7): 1746–1759. doi: 10.1007/s11814-023-1439-6
43. Shen H, Sun T, Zhou J. Recent progress in regenerated cellulose fibers by wet spinning. *Macromolecular Materials and Engineering* 2023; 308(10). doi: 10.1002/mame.202300089
44. Tan NPB, Cabatingan LK, Lim KJA. Synthesis of TiO_2 nanofiber by solution blow spinning (SBS) method. *Key Engineering Materials* 2020; 858: 122–128. doi: 10.4028/www.scientific.net/kem.858.122
45. Medeiros ES, Glenn GM, Klamczynski AP, et al. Solution blow spinning: A new method to produce micro- and nanofibers from polymer solutions. *Journal of Applied Polymer Science* 2009; 113(4): 2322–2330. doi: 10.1002/app.30275

46. Wu G, Du H, Cha YL, et al. A wearable mask sensor based on polyaniline/CNT nanocomposites for monitoring ammonia gas and human breathing. *Sensors and Actuators B: Chemical* 2023; 375: 132858. doi: 10.1016/j.snb.2022.132858
47. Scaffaro R, Settanni L, Gulino EF. Release profiles of carvacrol or chlorhexidine of PLA/graphene nanoplatelets membranes prepared using electrospinning and solution blow spinning: A comparative study. *Molecules* 2023; 28(4): 1967. doi: 10.3390/molecules28041967
48. Jeong C, Starr FW, Beers KL, et al. Influence of functionalization on the crystallinity and basic thermodynamic properties of polyethylene. *Macromolecules* 2023; 56(11): 3873–3883. doi: 10.1021/acs.macromol.2c02569
49. Fajardo-Diaz JL, Morelos-Gomez A, Cruz-Silva R, et al. Low-pressure reverse osmosis membrane made of cellulose nanofiber and carbon nanotube polyamide nano-nanocomposite for high purity water production. *Chemical Engineering Journal* 2022; 448: 137359. doi: 10.1016/j.cej.2022.137359
50. Patil PT, Anwane RS, Kondawar SB. Development of electrospun polyaniline/ZnO composite nanofibers for LPG sensing. *Procedia Materials Science* 2015; 10: 195–204. doi: 10.1016/j.mspro.2015.06.041
51. Ostheller ME, Balakrishnan NK, Beukenberg K, et al. Pilot-scale melt electrospinning of polybutylene succinate fiber mats for a biobased and biodegradable face mask. *Polymers* 2023; 15(13): 2936. doi: 10.3390/polym15132936
52. Yu DG, Li Q, Song W, et al. Advanced technique-based combination of innovation education and safety education in higher education. *Journal of Chemical Education* 2023; 100(2): 507–516. doi: 10.1021/acs.jchemed.2c00568
53. Chen J, Wang Y, Liu Y, et al. Fabrication of macroporous magnetic carbon fibers via the cooperative etching-electrospinning technology toward ultra-light microwave absorption. *Carbon* 2023; 208: 82–91. doi: 10.1016/j.carbon.2023.03.043
54. Nguyen TD, Roh S, Nguyen MTN, et al. Structural control of nanofibers according to electrospinning process conditions and their applications. *Micromachines* 2023; 14(11): 2022. doi: 10.3390/mi14112022
55. Huang Y, Duan Y, Ding Y, et al. Versatile, kinetically controlled, high precision electrohydrodynamic writing of micro/nanofibers. *Scientific Reports* 2014; 4(1). doi: 10.1038/srep05949
56. Jiang J, Liu Y, Chen J, et al. In-situ molding of micro three-dimensional columnar structure by electric-field-focused electrospinning. *Materials Today Communications* 2023; 35: 105589. doi: 10.1016/j.mtcomm.2023.105589
57. Akhoundi B, Modanloo V, Mashayekhi A. Design and manufacture of an additive manufacturing printer based on 3D melt electrospinning writing of polymer. *International Polymer Processing* 2023; 38(3): 424–433. doi: 10.1515/ipp-2023-4352
58. He X, Gu J, Hao Y, et al. Continuous manufacture of stretchable and integratable thermoelectric nanofiber yarn for human body energy harvesting and self-powered motion detection. *Chemical Engineering Journal* 2022; 450: 137937. doi: 10.1016/j.cej.2022.137937
59. Zhang P, Su J, Guo J, et al. Influence of carbon nanotube on properties of concrete: A review. *Construction and Building Materials* 2023; 369: 130388. doi: 10.1016/j.conbuildmat.2023.130388
60. Abubakre OK, Medupin RO, Akintunde IB, et al. Carbon nanotube-reinforced polymer nanocomposites for sustainable biomedical applications: A review. *Journal of Science: Advanced Materials and Devices* 2023; 8(2): 100557. doi: 10.1016/j.jsamd.2023.100557
61. Arjmandi SK, Khademzadeh Yeganeh J, Zare Y, et al. Development of Kovacs model for electrical conductivity of carbon nanofiber–polymer systems. *Scientific Reports* 2023; 13(1). doi: 10.1038/s41598-022-26139-5
62. Zahid M, Anum R, Siddique S, et al. Polyaniline-based nanocomposites for electromagnetic interference shielding applications: A review. *Journal of Thermoplastic Composite Materials* 2021; 36(4): 1717–1761. doi: 10.1177/08927057211022408
63. Noh YJ, Joh HI, Yu J, et al. Ultra-high dispersion of graphene in polymer composite via solvent freefabrication and functionalization. *Scientific Reports* 2015; 5(1). doi: 10.1038/srep09141
64. Simotwo SK, DelRe C, Kalra V. Supercapacitor electrodes based on high-purity electrospun polyaniline and polyaniline–carbon nanotube nanofibers. *ACS Applied Materials & Interfaces* 2016; 8(33): 21261–21269. doi: 10.1021/acsami.6b03463
65. Zhang F, Yang K, Liu G, et al. Recent advances on graphene: Synthesis, properties and applications. *Composites Part A: Applied Science and Manufacturing* 2022; 160: 107051. doi: 10.1016/j.compositesa.2022.107051
66. Yang H, Zheng H, Duan Y, et al. Nanocellulose-graphene composites: Preparation and applications in flexible electronics. *International Journal of Biological Macromolecules* 2023; 253: 126903. doi: 10.1016/j.ijbiomac.2023.126903
67. Chen L, Shen Y, Liu Z, et al. Experimental and modeling investigation on thermodynamic effect of graphene doped shape memory epoxy composites. *Polymer* 2022; 239: 124430. doi: 10.1016/j.polymer.2021.124430
68. Zhuang YF, Cao XY, Zhang JN, et al. Monomer casting nylon/graphene nanocomposite with both improved thermal conductivity and mechanical performance. *Composites Part A: Applied Science and Manufacturing* 2019; 120: 49–55. doi: 10.1016/j.compositesa.2019.02.019

69. Maccaferri E, Mazzocchetti L, Benelli T, et al. Morphology, thermal, mechanical properties and ageing of nylon 6,6/graphene nanofibers as Nano2 materials. *Composites Part B: Engineering* 2019; 166: 120–129. doi: 10.1016/j.compositesb.2018.11.096
70. Kausar A, Ahmad I, Eisa MH, et al. Manufacturing strategies for graphene derivative nanocomposites—Current status and fruitions. *Nanomanufacturing* 2023; 3(1): 1–19. doi: 10.3390/nanomanufacturing3010001
71. Weise BA, Wirth KG, Völkel L, et al. Pilot-scale fabrication and analysis of graphene-nanocomposite fibers. *Carbon* 2019; 144: 351–361. doi: 10.1016/j.carbon.2018.12.042
72. Leyva-Porras C, Ornelas-Gutiérrez C, Miki-Yoshida M, et al. EELS analysis of nylon 6 nanofibers reinforced with nitroxide-functionalized graphene oxide. *Carbon* 2014; 70: 164–172. doi: 10.1016/j.carbon.2013.12.087
73. Xu Z, Gao C. In situ polymerization approach to graphene-reinforced nylon-6 composites. *Macromolecules* 2010; 43(16): 6716–6723. doi: 10.1021/ma1009337
74. Zhang Y, Liu H, Liu M, et al. Effects of different amine-functionalized graphene oxide on the mechanical and thermal properties of polyimide composites. *High Performance Polymers* 2023; 35(9): 963–973. doi: 10.1177/09540083231199766
75. Afzal HM, Shehzad F, Zubair M, et al. Influence of microwave irradiation on thermal properties of PVA and PVA/graphene nanocomposites. *Journal of Thermal Analysis and Calorimetry* 2019; 139(1): 353–365. doi: 10.1007/s10973-019-08419-x
76. Mohd Abdah MAA, Zubair NA, Azman NHN, et al. Fabrication of PEDOT coated PVA-GO nanofiber for supercapacitor. *Materials Chemistry and Physics* 2017; 192: 161–169. doi: 10.1016/j.matchemphys.2017.01.058
77. Huo J, Zhang G, Yuan X, et al. Electrospraying graphene nanosheets on polyvinyl alcohol nanofibers for efficient thermal management materials. *ACS Applied Nano Materials* 2023; 6(7): 6241–6246. doi: 10.1021/acsanm.3c00563
78. Kadoshima T, Sakaguchi H, Eiraku M. Telencephalic tissue formation in 3D stem cell culture. In: *Organ Regeneration Based on Developmental Biology*. Springer; 2017. doi: 10.1007/978-981-10-3768-9
79. Jun L, Chen Q, Fu W, et al. Electrospun Yb-doped In_2O_3 nanofiber field-effect transistors for highly sensitive ethanol sensors. *ACS Applied Materials & Interfaces* 2020; 12(34): 38425–38434. doi: 10.1021/acsami.0c12259
80. Cao X, Wang T, Jiao L. Transition-metal (Fe, Co, and Ni)-based nanofiber electrocatalysts for water splitting. *Advanced Fiber Materials* 2021; 3(4): 210–228. doi: 10.1007/s42765-021-00065-z
81. Wang J, Wang C, Hou K, et al. Electrospinning of bitter gourd shape CoNiSe2@N carbon nanofibers as absorbers for electromagnetic wave attenuation. *Composites Part A: Applied Science and Manufacturing* 2023; 175: 107770. doi: 10.1016/j.compositesa.2023.107770
82. Li B, Yuan H, Zhang Y. Transparent PMMA-based nanocomposite using electrospun graphene-incorporated PA-6 nanofibers as the reinforcement. *Composites Science and Technology* 2013; 89: 134–141. doi: 10.1016/j.compscitech.2013.09.022
83. Abdali H, Ajji A. Preparation of electrospun nanocomposite nanofibers of polyaniline/poly(methyl methacrylate) with amino-functionalized graphene. *Polymers* 2017; 9(12): 453. doi: 10.3390/polym9090453
84. Ramazani S, Karimi M. Study the molecular structure of poly(ε-caprolactone)/graphene oxide and graphene nanocomposite nanofibers. *Journal of the Mechanical Behavior of Biomedical Materials* 2016; 61: 484–492. doi: 10.1016/j.jmbbm.2016.04.020
85. Bagheri M, Mahmoodzadeh A. Polycaprolactone/graphene nanocomposites: Synthesis, characterization and mechanical properties of electrospun nanofibers. *Journal of Inorganic and Organometallic Polymers and Materials* 2019; 30(5): 1566–1577. doi: 10.1007/s10904-019-01340-8
86. Ramazani S, Karimi M. Aligned poly(ε-caprolactone)/graphene oxide and reduced graphene oxide nanocomposite nanofibers: Morphological, mechanical and structural properties. *Materials Science and Engineering: C* 2015; 56: 325–334. doi: 10.1016/j.msec.2015.06.045
87. Suja PS, Reshmi CR, Sagitha P, et al. Electrospun nanofibrous membranes for water purification. *Polymer Reviews* 2017; 57(3): 467–504. doi: 10.1080/15583724.2017.1309664
88. Wypych G. *Functional Fillers: Chemical Composition, Morphology, Performance, Applications*. Elsevier; 2023.
89. Zhang F, Si Y, Yu J, et al. Electrospun porous engineered nanofiber materials: A versatile medium for energy and environmental applications. *Chemical Engineering Journal* 2023; 456: 140989. doi: 10.1016/j.cej.2022.140989
90. Xu X, Si Y, Zhao Y, et al. Electrospun textile strategies in tendon to bone junction reconstruction. *Advanced Fiber Materials* 2022; 5(3): 764–790. doi: 10.1007/s42765-022-00233-9
91. Chen K, Li Y, Li Y, et al. Stimuli-responsive electrospun nanofibers for drug delivery, cancer therapy, wound dressing, and tissue engineering. *Journal of Nanobiotechnology* 2023; 21(1). doi: 10.1186/s12951-023-01987-z
92. Mamun A, Kiari M, Sabantina L. A recent review of electrospun porous carbon nanofiber mats for energy storage and generation applications. *Membranes* 2023; 13(10): 830. doi: 10.3390/membranes13100830
93. Fan P, Ye C, Xu L. One-dimensional nanostructured electrode materials based on electrospinning technology for supercapacitors. *Diamond and Related Materials* 2023; 134: 109803. doi: 10.1016/j.diamond.2023.109803
94. Senthilkumar SH, Ramasubramanian B, Rao RP, et al. Advances in electrospun materials and methods for Li-Ion batteries. *Polymers* 2023; 15(7): 1622. doi: 10.3390/polym15071622

95. Widhiyanuriyawan D, Arifin Z, Muwaffaq A, et al. The effect of electrospinning precursor flow rate with rotating collector on ZnO nanofiber size results on double-layered DSSC photoanode fabrication. *Evergreen* 2023; 10(1): 504–509. doi: 10.5109/6782154
96. Zhang J, Liu J, Liu Y, et al. Design engineering of MOF-derived ZnO porous nanofibers functionalized with Pt clusters: Significantly improved acetone sensing properties. *Sensors and Actuators B: Chemical* 2024; 400: 134941. doi: 10.1016/j.snb.2023.134941
97. Liu J, Wang W, Li G, et al. Metal-organic framework-derived CuO tube-like nanofibers with high surface area and abundant porosities for enhanced room-temperature NO_2 sensing properties. *Journal of Alloys and Compounds* 2023; 934: 167950. doi: 10.1016/j.jallcom.2022.167950
98. Wang P, Lv H, Cao X, et al. Recent progress of the preparation and application of electrospun porous nanofibers. *Polymers* 2023; 15(4): 921. doi: 10.3390/polym15040921
99. Zhang H, Luo X, Shi K, et al. Nanocarbon-based catalysts for esterification: Effect of carbon dimensionality and synergistic effect of the surface functional groups. *Carbon* 2019; 147: 134–145. doi: 10.1016/j.carbon.2019.02.079
100. Zhou S, Zhang H, Zhao Q, et al. Graphene-wrapped polyaniline nanofibers as electrode materials for organic supercapacitors. *Carbon* 2013; 52: 440–450. doi: 10.1016/j.carbon.2012.09.055
101. Wang N, Wang B, Wang W, et al. Structural design of electrospun nanofibers for electrochemical energy storage and conversion. *Journal of Alloys and Compounds* 2023; 935: 167920. doi: 10.1016/j.jallcom.2022.167920
102. Barhoum A, Pal K, Rahier H, et al. Nanofibers as new-generation materials: From spinning and nano-spinning fabrication techniques to emerging applications. *Applied Materials Today* 2019; 17: 1–35. doi: 10.1016/j.apmt.2019.06.015
103. Liao HC, Ho CC, Chang CY, et al. Additives for morphology control in high-efficiency organic solar cells. *Materials Today* 2013; 16(9): 326–336. doi: 10.1016/j.mattod.2013.08.013
104. Howard JB, Noh S, Beier AE, et al. Fine tuning surface energy of poly(3-hexylthiophene) by heteroatom modification of the alkyl side chains. *ACS Macro Letters* 2015; 4(7): 725–730. doi: 10.1021/acsmacrolett.5b00328
105. Kurniawan M, Salim T, Tai KF, et al. Carrier dynamics in polymer nanofiber: Fullerene solar cells. *The Journal of Physical Chemistry C* 2012; 116(34): 18015–18022. doi: 10.1021/jp302968e
106. Loukelis K, Helal ZA, Mikos AG, et al. Nanocomposite bioprinting for tissue engineering applications. *Gels* 2023; 9(2): 103. doi: 10.3390/gels9020103
107. Navaratnam S, Selvaranjan K, Jayasooriya D, et al. Applications of natural and synthetic fiber reinforced polymer in infrastructure: A suitability assessment. *Journal of Building Engineering* 2023; 66: 105835. doi: 10.1016/j.jobe.2023.105835
108. Adapa SK, Jagadish. Prospects of natural fiber-reinforced polymer composites for additive manufacturing applications: A review. *JOM* 2023; 75(3): 920–940. doi: 10.1007/s11837-022-05670-w
109. Babu A, Aazem I, Walden R, et al. Electrospun nanofiber based TENGs for wearable electronics and self-powered sensing. *Chemical Engineering Journal* 2023; 452: 139060. doi: 10.1016/j.cej.2022.139060
110. Wang X, Hsiao BS. Electrospun nanofiber membranes. *Current Opinion in Chemical Engineering* 2016; 12: 62–81. doi: 10.1016/j.coche.2016.03.001
111. Cui J, Li F, Wang Y, et al. Electrospun nanofiber membranes for wastewater treatment applications. *Separation and Purification Technology* 2020; 250: 117116. doi: 10.1016/j.seppur.2020.117116
112. Zhao K, Tian X, Xing J, et al. Tunable mechanical behavior of collagen-based films: A comparison of celluloses in different geometries. *International Journal of Biological Macromolecules* 2022; 214: 120–127. doi: 10.1016/j.ijbiomac.2022.05.191
113. Saleem H, Trabzon L, Kilic A, et al. Recent advances in nanofibrous membranes: Production and applications in water treatment and desalination. *Desalination* 2020; 478: 114178. doi: 10.1016/j.desal.2019.114178
114. Tlili I, Alkanhal TA. Nanotechnology for water purification: Electrospun nanofibrous membrane in water and wastewater treatment. *Journal of Water Reuse and Desalination* 2019; 9(3): 232–248. doi: 10.2166/wrd.2019.057