Journal of Membrane
Science & Technology

Kamrani and Nosrati, J Membr Sci Technol 2018, 8:2
DOI: 10.4172/2155-9589.1000183

Review Article Open Access

# Fabrication of Nanofiber Filtration Membranes Using Polyethylene Terephthalate (PET): A Review

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## Abstract

Application of Polyethylene Terephthalate (PET) in membrane technology for fabrication of nanofiber filtration membranes for water treatment has gained increasing attention in recent years. Some new studies focusing on the application of recycled PET nanofibers in membrane structure have also been reported. Currently, many different chemical and physical methods are being used for water purification. However, membrane technology is becoming more popular and desirable in both domestic and industrial applications. This mini review paper aims to summarize (i) recent developments in synthesis of nanofiltration membranes using PET nanofibers, (ii) some of their different applications for water treatments, and also (iii) survey a new method in membrane fabrication technology for the first time using electrospining technique coupled by Vortex Fluidic Device (VFD) as a new platform for the better membrane fabrication process.

**Keywords:** Membrane fabrication; Membrane; Nanofiber; Electrospining technique

**Abbreviations:** PET: Polyethylene Terephthalate; VFD: Vortex Fluidic Device

## Introduction

Conservation of water resources is one of the most important current environmental issues which has brought a controversial debate in public discussions in recent years and gained attention of international organizations such as conservation nature and natural resources reservation [1]. Water purification and recycle are also other important challenging problems around the world as without clean water resources the human life will be in danger. To address these challenges, different water purification methods including membrane filtration have been used extensively in recent decades [2,3]. Some other costly and complex technologies have also been developed for purification of salty or saline and drain water resources [4-6]. However, the most rational solution at the moment is conservation of existing sweet water resources [7]. Taking into account that only 0.5% of the total accessible world water is fresh water, desalination of sea water is a costly purification technique that is performed in places that sweet superficial water is not accessible [8].Water purification is also being considered even in places where the preserving sweet water resources can be achieved by some simple methods such as construction of different types of dams [9]. To date, there have been many studies and efforts for development of new methods for purification of dirty harmful water, containing contaminants or microorganisms, into clean safe water [10-14]. These methods usually use nanomaterials such as nanoparticles, nanofibers, nano thin films, Zeolites, carbon nanotubes, etc. [15]. Today, other different water treatment and purification methods for the cleaning of water have been developed with the most common ones being i) Chemical methods such as coagulation, flocculation, flotation, chlorination, filtration, chemical precipitation and ion exchange [16-22], ii) Biological treatments and Biodegradation methods such as microbial biomass adsorption [23], microbial degradation [24] and biodesalination [25], and iii) Adsorption techniques involving solid sorbents such as Carbon Nanotubes (CNTs), activated carbon and carbon fiber [26-29]. Amongst all above mentioned classic techniques, adsorption with solid adsorbents is a simpler and cheaper method for water pre-treatment and cleaning. However, one important environmental concern for this method is the necessity for the adsorbent to be environment-friendly, nontoxic and easily removable from reaction media after the consumption. Thus, their toxicity performance and heterogeneity must be considered strictly before their application in industry [16,30]. For example, in water desalination using some nano-composites such as $TiO_2$-Cu thin films, the consumed thin film can be removed easily from aqueous matrix without any water pollution after its usage [31].On the other hand, between all well-developed not classic techniques, Membrane filtration is a high-tech effective method for water treatment [11]. In membrane-based water filtration, the membrane is usually a highly porous polymeric thin film or a blend of nanofibers that has the ability of removing very small water pollutants. Different types of membrane filtration include Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), Reverse Osmosis (RO) and Membrane Distillation (MD) [32]. The difference between UF and MF with RO is that UF and MF are commonly used for drainage water treatment that has been used before and need to be refined, while RO is widely used for unused water desalination and also purification. MD is a newer developing technique for desalination of saline water [33,34]. A brief information about different water purification techniques is shown in Table 1 indicating that membrane technology is preferable technique for water purification compared with other techniques [31] (Table 1).

Hence, only this method is discussed in the remaining parts of this paper. Some striking properties of polymeric water filtration membranes have provoked researchers to investigate different polymers in this field. The properties such as hydrophilicity, flexibility in

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**Received** May 28, 2018; **Accepted** June 20, 2018; **Published** June 30, 2018

**Citation:** Kamrani H, Nosrati A (2018) Fabrication of Nanofiber Filtration Membranes Using Polyethylene Terephthalate (PET): A Review. J Membr Sci Technol 8: 183. doi:10.4172/2155-9589.1000183

| Applications | Examples of nanomaterials | Some of novel properties |
|---|---|---|
| Adsorption | CNTs/nanoscale metal oxides and Nanofibers | High specific surface area and assessable.<br>Adsorption sites, selective and more.<br>Adsorption sites, short intra-particle diffusion distance, tunable surface chemistry, easy reuse. |
| Disinfection | Nanosilver/titanium dioxide (Ag/$TiO_2$) and CNTs | Strong antimicrobial activity, low toxicity and cost, high chemical stability, ease of use. |
| Photocatalysis | Nano-TiO2 and Fullerene derivatives | Photocatalytic activity in solar spectrum, low human toxicity, high stability and selectivity, low cost. |
| Membranes | Nano-Ag/$TiO_2$/Zeolites/Magnetite/fibers and CNTs | Strong antimicrobial activity, hydrophilicity, low toxicity to humans, high mechanical and chemical stability, high permeability and selectivity, photocatalytic activity. |

**Table 1:** Comparative information about common water treatment techniques [31].

fabrication, low cost, high thermal resistance, wide pH tolerances, high mechanical characteristics and other aspects make them good target for membrane technology [34]. As a specific case, PET membrane along with its different fabrication methods and various applications especially in modified form for water treatment will be considered as main issues. Some great properties such as non-toxicity, strength, lightweight, safety, flexibility make PET to a very important and useful raw material that is recognized 100% recyclable globally. Figure 1 shows the structure of PET polymer which is the most common clear plastic that is used anywhere as domestic consumptions like soda bottle containers (Figure 1).

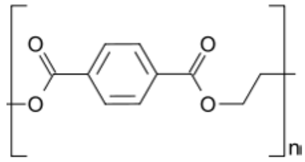

**Figure 1:** The chemical structure of PET [35].

But PET film compared with bottle form can be a good target for other industrial applications such as membrane filtration technology. The structure of PET having polar groups like oxygen seems to develop a high selective membrane in coupling with specific chemical or biochemical reagent for contaminant removal [35].

## Different previous methods for PET membrane synthesis

Membrane filtration in different forms like polymeric nanoporous thin film or nanofibers with various capabilities are being used in different scales. It is extended from domestic to industrial scales especially for water or wastewater treatment such as industrial wastewater revitalization. It is applied also for water recycle, water softening and cleaning, and separation of compounds having different molecular weights such as different organic or inorganic pollutants. Concerning to the structure of nanofibers or nanopores, the design of nanofiltration membranes with maximum permeability, selectivity and resistance to fouling with optimum pore structure and fibers diameter is very important [34]. Supposed to the third initial aims of this paper, VFD application for PET membrane fabrication in solution form coupled solution electrospining technique will be considered. The output of VFD will be more homogenous PET solution that will be charged into electric field and the result will be more uniform nanofibers. Thus nanofiber membrane filtration will be the basis of discussion for membrane fabrication. The other advantage of nanofiber compared with nanopores is included in high ratio of surface area to its volume that makes it preferable. In this section various methods for PET membrane fabrication are reviewed. The idea of PET membrane usage in water treatment has heightened the investigation of narrow and more innovative studies in membrane technology. The key properties of PET such as stability in acids and organic solvents as well as mechanical resistance have made it the most commonly used material for polymeric membrane fabrication using techniques such as track etching and electrospining [35]. One advantage for application of PET in membrane fabrication rather than other polymers can be the utilization of recycled bottle grade PET as a waste material instead of virgin samples. This is due to the fact that there are no significant differences between virgin and recycled PET samples in terms of physical or chemical properties [36]. Hence, it would be very valuable to vast this technology to both recycled and pure PET instead of just virgin samples. By application of recycled bottle grade PET, not only an environmental pollution problem can be solved, but also fabrication of nanofibers for membrane usage will be achieved at lower cost.. Before application of recycled PET for nanofiber fabrication, it is necessary to consider its physical properties compared with pure or virgin PET samples. In one study by Lee [36], the similarity of recycled PET and virgin PET and their chemical and physical properties was investigated. The result showed no difference in physical properties between recycled PET and virgin samples. It was also determined that chemical and tensile properties of recycled PET are similar to virgin PET [36]. Brennan [37] also studied the properties of fresh and recycled Polystyrene (PS) where there was negligible difference between their mechanical and thermal properties [37]. The same result was also observed for fresh and recycled Polycarbonate (PC) in other studies [38,39]. These and other similar studies suggest that there will not be physical restrictions for the usage of recycled polymers like PET for nanofiber membrane fabrication if their extrinsic contaminants are completely removed. A recent study on recycled PET (rPET) by Zander proved the possibility of rPET for nanofiber fabrication. They proved that the mechanical properties of the recycled PET fibers using microtensile tests show the elastic module range from 15 to 60 MPa, and in equivalent molecular weight their hardness are comparable or greater than fibers made from commercial polymers [40]. In the following section two main fabrication techniques that are more common for PET membrane fabrication will be explained (i) Electrospining and (ii) Tracked-Etching techniques.

### Electrospinning method

Electrospining method is the first mostly useable and comparatively newer method that is applied for porous membranes including nanofiber filtration membranes [41-43]. This method is divided to two categorizes based on polymeric state during injection to the electric potential; (i) Melt electrospining and (ii) Solution electrospining method. In melt electrospining, first polymer melts and then a charged liquid jet is formed in presence of electrostatic potential to produce nanofiber threads. Electric force is sufficient to overcome the surface tension of droplets. In solution electrospining, first polymer is dissolved in an appropriate solvent and then a charged liquid jet is formed and finally nanofibers are produced that is shown in Figure 2 [34].

According to Tylor [44], fabrication of nanofiber charged threads from drawing viscose melt or liquid droplet is related to maximum instability of the liquid surface induced by the electrical forces. So the

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control of electrical force is very important. In a study by Zander et al. solution electrospining method was used to fabricate nanofiber from recycled bottle grade PET for water filtration to remove microbial contaminants. The estimated diameter of produced PET nanofibers was ~500 nm and could just filter the particles larger than 500 nm. Filtration and antimicrobial tests showed a good result where >99% of the beads as small as 500 nm were removed using gravity filtration of water (Table 2).

This was a study which for the first time used recycled bottle grade PET (rPET) for water filtration as membrane filtration and the results were remarkable. Hence, for better efficiency the fibers were functionalized with biocidal materials to reduce biofouling [45]. Before this study, the initial idea of recycled bottle grade PET application for making nanofibers by Melt-electrospinning method was developed by Rajabinejad. In this study, first consumed PET bottles were crushed and cleaned and then melt electrospining method was used for nanofiber fabrication. The SEM images showed that the diameter of nanofiber was approximately between 61-93 nm [46]. In another study solution electrospining process was used to synthesize nano/microfibers of PET, Polystyrene (PS) and Polycarbonate (PC) from the relevant waste plastics and the effect of the used needle diameter and different voltages was considered .The results showed that the average pore diameter size depended on used voltages [47]. A recent review paper has summarized some previous information about Electrospun membranes and some recent developments of membrane technology and their potential impact in two major areas, i.e., desalination and water/wastewater treatment. It involved a summary of previous works on different electospun polymeric membranes and a glimpse about PET membrane as an example [48]. According to mentioned studies, it can vast all studies for the usage of recycled PET the same as pure PET samples because both precursors have same behaviour against fiber fabrication with electrospining method. In the following part, the focus of subject is about virgin PET membrane fabrication.

**Track-Etching method**

The other common and simpler technique for nanoporous not nanofiber PET fabrication that can be used for water membrane is track-etching technique that is shown in Figure 3. The Track-etching process is based on the irradiation of a material with swift heavy ions and subsequent chemical etching that makes pores on polymer texture [34]. Wang used the track-etched technique to fabricate PET polymer membranes as one part of a pumping media with low-voltage and high flow rate property. These kind of pumps that are known as low-voltage

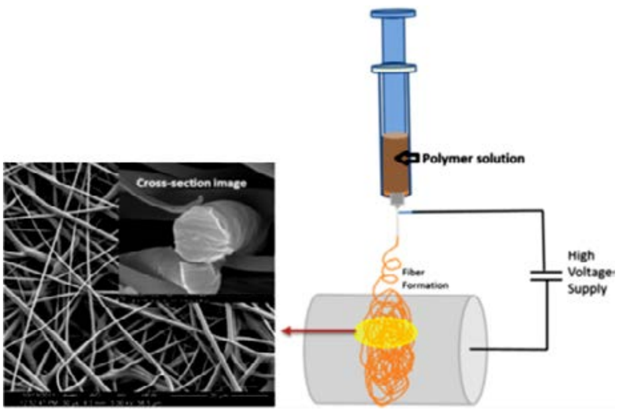


**Figure 2:** Schematic diagram of electrospining of polymer solution [34].

| | Percent captured | | | | |
|---|---|---|---|---|---|
| Wt.% rPET | 2 µBeads | 1 µBeads | 0.5 µBeads | 0.1 µBeads | 0.2 µBeads |
| 5 | 99.7 ± 0.07 | 99.7 ± 0.01 | 99.3 ± 0.9 | 21.1 ± 6.2 | 1.64 ± 0.7 |
| 7.5 | 99.4 ± 0.3 | 99.3 ± 0.1 | 70.6 ± 4.3 | - | - |
| 10 | 89.9 ± 4.1 | 49.3 ± 19.2 | 27.8 ± 7.4 | - | - |

**Table 2:** Filtration efficiency of recycled PET nanofibers determined by fluorescence Spectroscopy about different bead sizes [45].

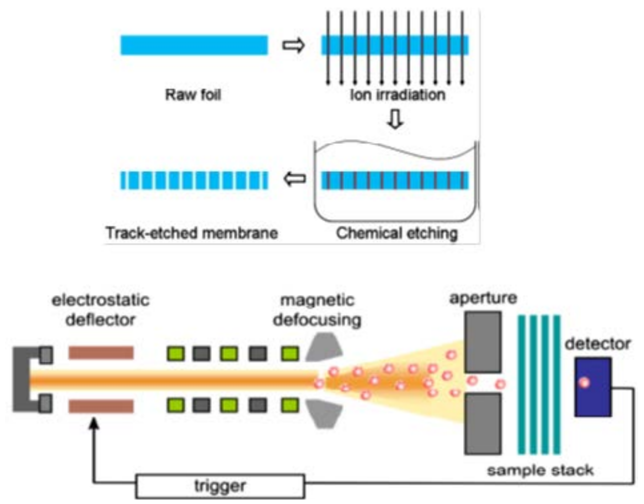


**Figure 3:** A Scheme of single ion-irradiation used to fabricate track etched membrane [34].

electro-osmotic EO pumps have been suggested to be used in many applications including High Performance Liquid Chromatography (HPLC), micro flow injection analysis, water management in fuel cells, microelectronic equipment cooling, drug delivery, etc. The pore diameter of PET film was in the range of 100 to 250 nm by regulation of the etching time. EO pump is assembled by two chambers separated by the PET track etched polymer membrane shown in Figure 4 [49].

In another study by Komaki porous PET films were prepared by thermal neutron fission of Uranium-235 radiation and the effect of etching rate on the pore diameter and density on membrane surface was studied. The effective pore diameters were between 10-100 nm and pore densities approximately 108 $cm^{-2}$ [50]. Another study was reported by Kravets for fabrication of a modified PET membrane in polymeric layer shape obtained by deposition of acetylene on the surface of PET membrane. The process was started by irradiation of PET film by accelerated Krypton ion at a cyclotron. Then ion-irradiated film again was irradiated by ultraviolet light in maximum wavelength at 310 nm. The final procedure was followed by chemical etching resulting in nanofibers' pore diameter of meanly 26 nm. It was concluded that some parameters can influence membrane characteristic that are summarized in Table 3 [51].

Zhang [52] reported a method for fabrication of Nanochannels in different polymer membranes by track-etching technique. In one part of this study both sides of PET thin film first were irradiated with UV light 60 min in 365 nm wavelength and then the etching process with single-ions and related chemicals performed to produce nanofiber (nanochannel) with 350 nm diameter. As a comparative information, different shape of PET nanochannels with different etching conditions were produced as shown in Figure 5 and the result are summarized Table 4.

The SEM images showed 350nm diameter of produced nanofibers [52]. Sartowska [53] also reported that by the controlled usage of surfactant on the surface of PET film the formation of asymmetric nanopores in PET film will be possible. This result was achieved first by photo oxidation with accelerated heavy Xe-ions irradiation in one side and the next extra UV irradiation on the other side of PET film. This caused the side with UV light exposure became less susceptible for surfactant adhesion because of photo oxidation. In continue diffusion of alkali on this side became higher that formed asymmetric PET nanopores. So these two factors; Chemical attack of alkali solution and surfactant effect can control asymmetric nanopores formation in PET film that is shown in Figure 6.

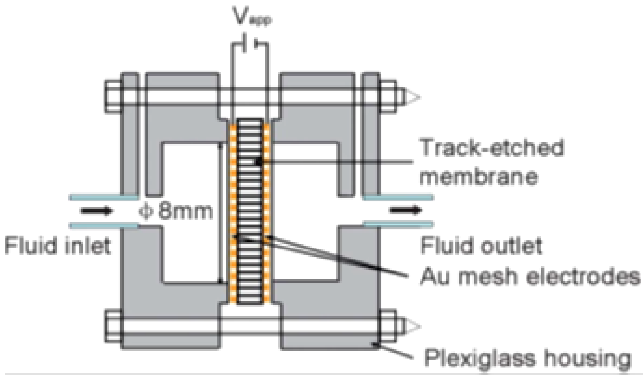


**Figure 4:** Schematic of the EO pump fabricated from track-etched membrane. The pump has a 130 mm thick and 0.5 cm$^2$ active cross-sectional area [49].

| Parameter | Initial membrane | Plasma treatment time (s) | |
|---|---|---|---|
| | | 300 | 600 |
| Relative increase in the mass (%) | - | 3.7 | 8.2 |
| Thickness of deposited layer (nm) | - | 70 | 150 |
| Air flow rate at $\Delta P=3 \times 10^4$ Pa (ml/min cm$^2$) | 165.0 | 95.0 | 10 |
| Effective pore diameter (nm) | 65.0 | 54.5 | 26 |
| Water contact angle (degree) | 65 | 67 | 65 |

**Table 3:** Change in the membrane characteristics during treatment by acetylene plasma [51].

As it was summarized in this section, two main methods for PET membrane fabrication were electrospining and track-etching methods that have better and more effective results. Although previous studies prove that electrospining and track-etching are the best methods for membrane fabrication from rPET or virgin PET, Zander [54] tried to use a different rPET membrane fabrication method. They assessed the possibility of nanofiber fabrication from rPET bottle grade using a Centrifugal Spinning Technique (CST) which is completely different from electrospining method. In CST, polymeric fibers are made by heat source with centrifugal power rather than high voltage in electrospining method. The fabricated fibers have micro size not nanosize diameter without conductivity and solubility in any chemicals. This study involved three different polymers, polypropylene, polystyrene and PET. The results confirmed that all recycled polymer nanofibers show significant capabilities in filtration, textile industry and insulation. SEM images proved that fabricated nanofibers with CST have smooth surface with diameters between 1070-9410 nm that is enough for water pre-treatment and contaminant filtration. Overall, this study shows that PET nanofiber membrane can be applied at least for water pre-treatment easily, however, further work and using chemicals or biochemical additives is required to make it applicable for specific water purification purpose. For instance, according to Trofimov [55] track-etch modified PET membrane in presence of N-isopropylacrylamide (NIPAM) solution as grafting agent and argon plasma matrix was produced in 30-40°C and the efficiency of water filtration was about 2.5 times more than original track membrane. The scheme of PET modification is shown in Figure 7.

## Modified PET nanofiber filtration membranes for specific water treatment applications

PET membrane modification with some chemical or biochemical groups converts it to a more selective tool that can be used for specific applications [56-61]. This part includes a brief assessment of the effect of PET surface modification on PET membrane quality. Recently there have been some novel studies on desalination of water using surface modified PET membranes. For instance Fang [62] could modify PET

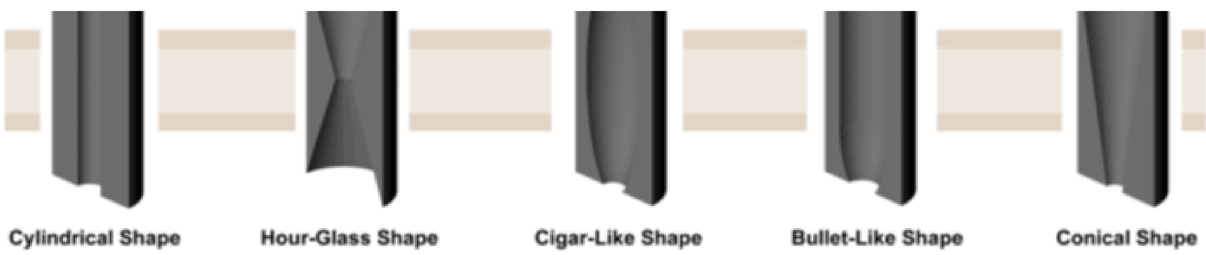


**Figure 5:** Different artificial symmetric and asymmetric PET nanochannel with different etching conditions [52].

| Polymer | Etchant | Stopping Solution | Temperature |
|---|---|---|---|
| PET (Conical shape) | 9 M NaOH | 1 M KCl or mixture of 2 M KCl and 2 M HCOOH (1:1 by volume) | ~23°C |
| Polyimide (PI) (Conical shape) | NaClO solution of initially high pH value (12.6) with an active chlorine content of 13% | 1 M KI | ~50°C |
| Polycarbonate (PC) (Cylindrical shape) | 6 M NaOH (both sides) | - | ~60°C |

**Table 4:** The Conditions of different etching processes for different nanochannel membranes [52].

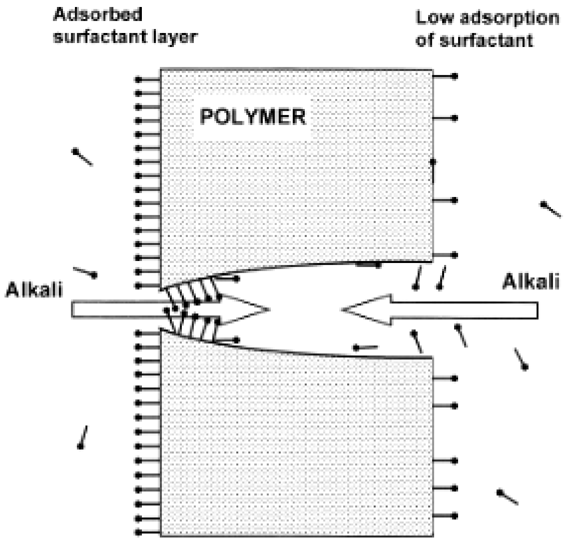


**Figure 6:** Scheme of track etching in an ion-irradiated polymer film in the presence of nano-sized surfactant molecules [53].

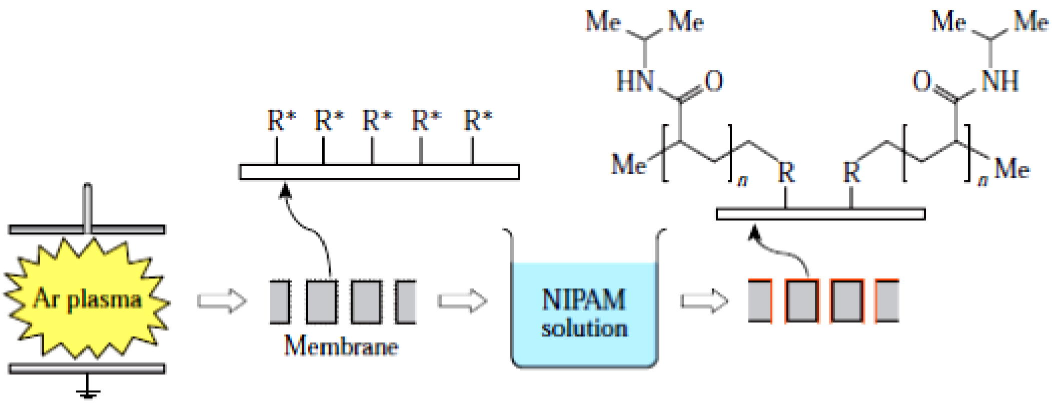


**Figure 7:** Schematic diagram of PET membrane modification by track-etching process in Arpalasma matrix and NIPAM solution [55].

electrospun nanofibers with natural proteins, such as gelatin and collagen to produce gelatin-grafted PET nanofibers. This study showed apparent enhancement in the spreading and proliferation of vascular endothelial cells on modified PET nanofibers' surface compared with the non-grafted ones. In another study, the effect of polyvinyl pyrrolidone (PVP) on the characteristic of modified membranes made from recycled PET bottles for humic acid removal was investigated. Porous polymeric membranes were prepared via thermally induced phase separation by dissolving recycled PET bottles in phenol. For modified PET membrane, a 5% wt of PVP was added into PET solution and the final solution was dried slowly at room temperature to solidify the membrane. The tests of humic acid removal from water showed about 75% rejection by PET-PVP modified membrane compared with pure PET with 25% humic acid rejection [63]. In a recent study, Kim [64] tried to mimic the desalination characteristics of mangrove roots as a natural membrane for fabrication of PET membrane. By inspiration of natural mangrove roots activity, a modified PET membrane in presence of polyelectrolytes using a layer-by-layer deposition technique was constructed that showed a high sodium ions desalination rate of 96.5 compared with 62% non-modified PET membrane. Abdel-Hady [65] introduced a commercial PET membrane for fuel cell application based on proton exchange (PEM) that is much better than Naf ion membrane that was applied in previous fuel cells. It was for better application of methanol as fuel cell energy generator instead of fossil fuel cell. PET membrane was a good representative in fuel cells as proton transferring agent in electrolyte, as well as a barrier to the passage of electrons between the electrodes. It can be used in automobile, residential homes, and in portable devices such as laptops and cell phones. Direct Methanol Fuel Cells (DMFCs) are also environmentally friendly compared with fossil cells. For preparation of PET-PEM, PET film was grafted by Styrene in presence of UV radiation and at the end sulfonation of grafted copolymer was performed. The effect of Styrene monomer concentration and irradiation time was tested and optimum percent of Sulfonation and ion exchange capacity was evaluated. Some factors like water uptake, proton conductivity, methanol permeability, sulfonation, ion exchange capacity and tensile strength were tested. Due to better proton conductivity and ion exchange with PET grafted membrane, it can be used in methanol fuel cell with lower cost, higher conductivity, suitable water uptake and low methanol permeability. Uyar [66] used cyclodextrin to modify PET nanofibers surface to improve its ability for phenanthrene removal from aqueous solution. The basic method for PET nanofiber production was solution electrospinning that was performed by dissolution of 22.5% (w/v) PET polymer in Tetrafloro acetic acid Dichloromethane (50/50, v/v) mixture and the next injection solution into an appropriate potential field. For modification process, the surface of the electrospun PET nanofibers was modified through the grafting reaction between PET and Cyclodextrin (CD). This step was done first by mixture of cyclodextrin solution with citric acid as crosslinking agent and sodium hypophosphite hydrate as catalyst. Then electrospun PET nanofibrous mats were dipped into the resulting solution and kept for 3 h at 50°C. The last product after washing was an effective modified PET nanofibers with a higher ability for phenanthrene removal from water compared with pure PET nanofibers. Figure 8 shows the steps of PET nanofiber modification with cyclodextrine.

In another study, Polyethersulfone (PES) nanofibers (260 ± 110 nm in diameter) were deposited on non-woven PET fibers [67]. The results showed that PES-PET membrane had more mechanical strength because of PET addition and was used for pre-filtration in removal of particles such as E. coli bacteria from water. However, a heat treatment was performed to improve its interfacial stability [67]. Ma [68] fabricated a modified Polyacrylonitrile (PAN)/PET membrane and used two ionic liquids namely, 1-butyl-3-methylimidazolium chloride and 1-ethyl-3-methylimidazolium acetate as solvents to help coating of poorly soluble cellulose on the surface of PAN/PET membrane under mild conditions. The membrane was tested for separation of oil and water mixture and proved higher flux potential with same rejection compared with commercial Ultrafiltration (UF) membrane. In another similar study, Guoliang Li [69] synthesized a PET enhanced cellulose acetate membrane by phase inversion method, where the effect of some parameters such as concentration and temperature of casting polymer solution, temperature and time of evaporation, coagulation and annealing process on membrane performance was evaluated. The produced membrane was tested for salt rejection with appropriate NaCl concentration as a feed solution and glucose as a draw solution showing a good water flux L/($m^2$•hr) and high salt rejection in Forward Osmosis (FO) mode [37]. In another innovative study not for water treatment, electrospun PET non-woven filter mat was applied to apple juice clarification. The final result of produced membrane was a random fibrous arrangement free of beads and high tri-dimensional porous structure with small pore diameters (the average fiber diameter was 420 nm). This new process showed a high flux performance and appeared to be much faster, simpler and more economical than the traditional clarification methods [70]. Jianguo [71] also modified the surface of PET thin film by nano $TiO_2$ particles with low gamma ray plasma to produce a new metalized and polarized PET membrane film with higher resistance to deformation and degradation and higher surface hydrophilicity than commercial PET film [71]. By consideration of all previous laboratory works it becomes clear that these works are very precious but are in small scale and is very important to develop to industrial scales too.

## A new synthetic PET nanofiber membrane idea using VFD

VFD is a novel microfluidic processing platform developed by Colin L. Raston [72]. It involves a rapidly rotating tube that is open in one end and can produce dynamic thin films at high rotational speed for finite sub-millilitre volumes of liquid set with different rotating angle. The shear in the result thin film depends on the speed and orientation of the tube. It works in two modes, continuous flow mode and confined mode. In continuous flow mode, at least two jet feeds inject one or more liquid reactants directly to the closed end of tube under different rotational angles and speeds and provides additional tunable shear and at the same time with the accomplishment of the reaction, the product exits from the tube. Continuous flow devices can facilitate conversion of small scale production to industrial production. It also minimizes waste and energy usage, and in high quantity production can be essentially safer [73]. In confined mode unlike continuous mode, there is not a continuous exiting of products at the top of the tube. Instead, a finite volume of one or more liquid reactants is filled into the tube and under a moderate rotational speed, a vortex of products maintain at the bottom of the tube and after accomplishment of reaction, the product is extracted. This is very similar to simple centrifuge but the only difference is that it can be performed under different angle and extended shearing time and therefore the reaction and its efficiency can be controlled with the balance of gravity and centrifugal force [74]. In the Figure 9 it is shown both VFD working modes.

The Figure 10 shows a scheme of continuous flow mode of VFD and the relationship between the speed of tube rotation and film thickness in a specific rotation angle. As the Figure 10 shows, with increasing in speed in continuous flow mode, the thickness of thin film in a specific angle rotation will decrease.

The main striking VFD advantage opposed to batch processing, where reactions are carried out in a pool of mixture of reactants such as ordinary centrifuge, is dynamic thin films formation that enables intense micro-mixing of the reactants producing effective surface waves within the thin film. The important result will be efficient heat and following mass transfer [75]. Raston [76] have done concentrated researches in application of VFD in different works. In an interesting research VFD was used for controlling reactivity and also selectivity of Diels-Alder reaction as an example. The application of VFD for accelerating organic dimerization reaction of cyclopentadienes, and following aldol and Michael addition reactions, in presence of unusual 2,4,6-triarylpyridines was investigated. Residence times were controlled for continuous flow processing with the viscous flow rates 0.1 mL/min in a 10 mm diameter tube rotating at 2000 rpm. The results are shown in Figure 11.

The results were very interesting and the role of VFD was clear [76]. In another following research by Raston [77] using optimized VFD, the controlling of chemical selectivity and reactivity was investigated. Accordingly, the parameters that were effective for controlling of reaction such as rotational speed, tilt angle, flow rate of injection, temperature and concentration of reactants were investigated. In confined mode the optimum condition for the reaction of cyclopentadiene dimerization was achieved in θ=45° and 90° with 7000 rpm speed and for 1 hour. Therefore, the only changeable parameter for controlling of optimum condition was tilt angle. But in continuous mode concurrently two parameters were changed and the optimum condition was achieved. In first experiment, rotation speed and tilt angle were changed and the results were followed. The optimum condition was in θ=90° and 9000 rpm with 0.1 mL/min flow rate. In other experiment two other parameters; flow rate and tilt angle were changed and the results were observed. The optimum condition was achieved in θ=45° and 0.1 mL/min flow rate with 7000 rpm. So related to wanted condition, one of these two modes would be selected. Some other narrative researches that have been performed with the help of VFD are involved bacteria and algal cells with graphene and magnetic polymer [78-80], protein folding [81], exfoliating single layered graphene and hexagonal Boron Nitride (h-BN) sheets from the bulk material [82], sol-gel synthesis of silica xero gel at room temperature and the incorporation of curcumin, [83] controlling the pore size and wall thickness of mesoporous

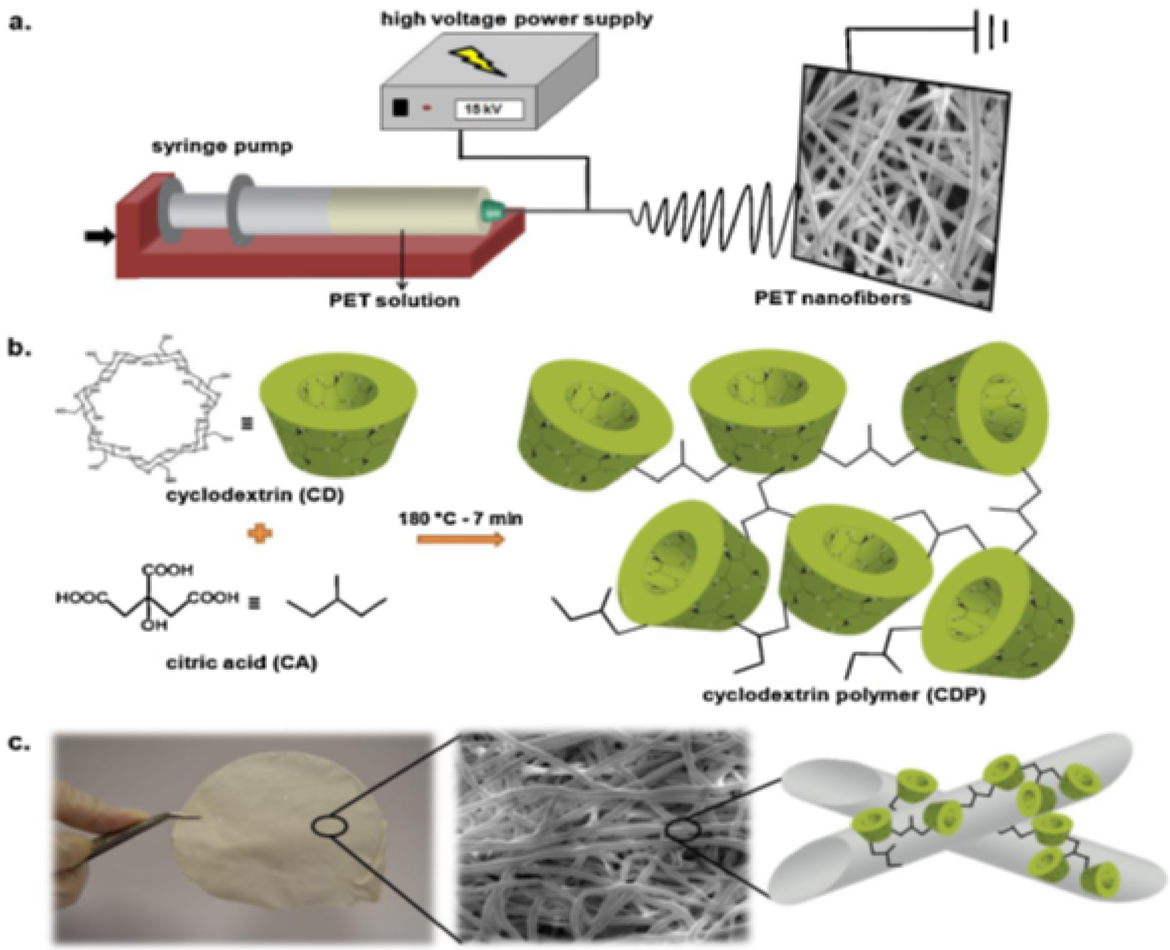


**Figure 8:** Schematic representations of (a) electrospinning of PET nanofibers, (b) the mechanism of CDP formation and (c) a photograph of PET/CDP nanofibrous mat and its SEM image with a schematic figure of PET/CDP nanofibers [67].

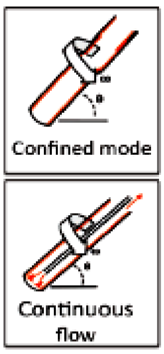


**Figure 9:** Scheme of continuous flow and confine mode of VFD [73,74].

silica [84,85], fabricating toroidal arrays of SWCNTs, [86] laterally 'slicing' CNTs, [87] accelerating enzymatic reaction, [88] probing the structure of self-organized systems [89,90], biodiesel catalysis [91] and many others. According to the extra capabilities of VFD as a various reaction media compared with Spinning Disc Processors (SDPs) or Rotating Tube Processors (RTPs), VFD will be more advantageous in reaction accomplishment [92]. It seems that it is also a good idea to apply VFD for better making of polymeric solution. For example, we can use PET solution with VFD continuous flow mode and finally the complete homogenous PET solution is charged to an electric force with enough voltage (solution electrospining) to produce better uniform and higher quality nanofiber. Even for specific application we can modify PET solution in VFD with the conjunction of specific chemical or biochemical groups to prepare PET solution and result thin film. Finally with optimization of VFD condition, the best quality concurrently high quantity of nanofiber membrane for water filtration would be achieved.

## Conclusion

The first aim of this mini review was PET and also modified PET membrane fabrication with different methods for water treatment application. The second intention was probable application of VFD as a new device for synthesis of PET membrane as a first idea. The new VFD application idea can optimize the production of a commercial membrane with more probable homogenous and higher quality of nanofibers. Further ,we can also apply VFD for recycled PET (rPET) solution production to fabricate low cost high quality membrane .Lower energy consumption and faster reaction with smaller effective volume of reactants during membrane fabrication are other positive results of VFD usage too. At the end the final purpose of recycled bottle grade

**Citation:** Kamrani H, Nosrati A (2018) Fabrication of Nanofiber Filtration Membranes Using Polyethylene Terephthalate (PET): A Review. J Membr Sci Technol 8: 183. doi:10.4172/2155-9589.1000183



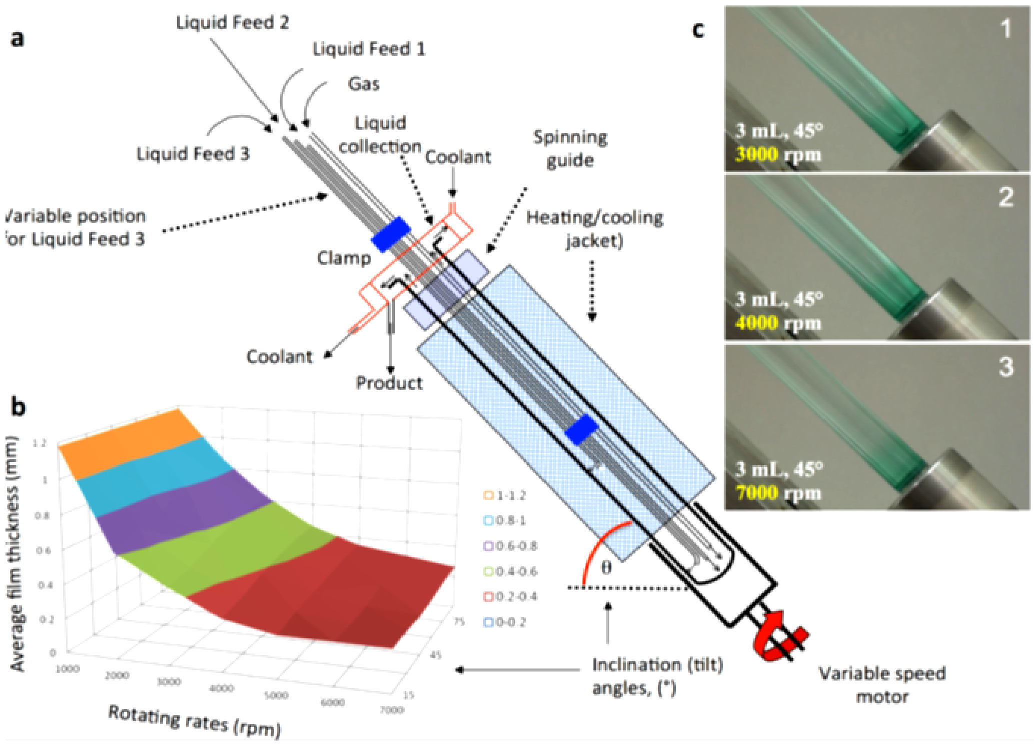


**Figure 10:** Vortex Fluidic Device (VFD). (a) Cross section showing components of the device; (b) Average film thickness (mm) versus tilt angle (θ); and rotating rates (c) Photographs showing the film of liquid developed for different speeds, for 3 mL of an aqueous solution, for θ =45° [77].

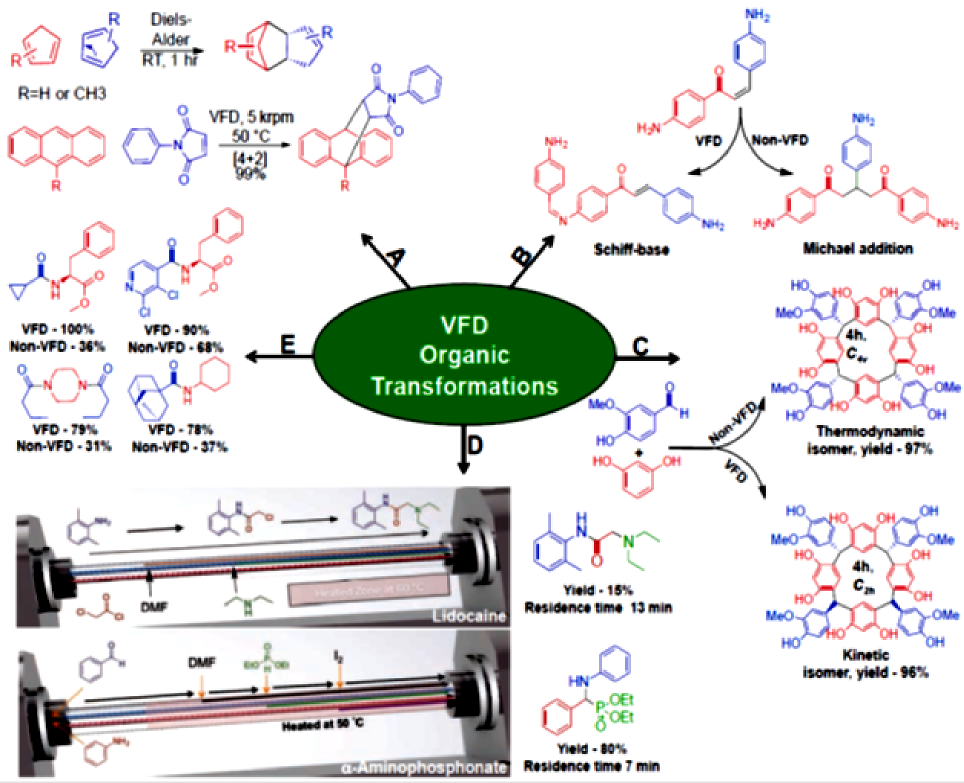


**Figure 11:** Different reactions with and without VDF application with different followed products [78].

PET usage for fabrication of PET membrane would help environment conservation effectively.

## Conflict of interest

None.

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