Review

Methods in Improving the Mechanical Properties and Flux of Nanofibre Membranes for Water Filtration

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Abstract: Nanofibres have gained increasing attention due to their advantages of having a high porous structure, narrow pore size and distribution, and a high specific surface area. One of the most efficient techniques for producing nanofibres is via electrospinning. Nanofibres are currently being used in various fields, including water filtration. Although nanofibres possess the ability to filter various components, the fibres generally have a low mechanical strength that can mitigate the performance over time. Therefore, in overcoming this issue, several studies have focused on improving the strength of the nanofibre membranes for a water filtration application. This review discusses the advantages and challenges of nanofibres for water filtration membranes and summarises the methods to increase the strength of the membranes, including solvent vapour, thermal treatment, and chemical crosslinking.

Keywords: Nanofibres; membranes; water filtration; vapour; chemical

1. Introduction

In the world of nanomaterial, nanofibres stand out as one of the most promising materials with diameters ranging from tens of nanometers to less than 1 micrometre [1,2]. The popularity phenomenon of nanofibre is mainly for its striking features, which are a high surface area to volume ratio and high porosity that makes them a robust and attractive candidate for many advanced applications [1]. Other features, such as morphology, high aspect ratio of length to diameter, and high molecular orientation along the fibre axis [3] can be configured and produced by manipulating the materials [1], solution parameters, electrospinning process, and environmental variables [4]. Most of these parameters are correlated with one another. Some of the methods to produce nanofibres are by wet spinning, dry spinning or melt spinning, template synthesis, solution blow spinning, and force spinning, but the most efficient and common way is through electrospinning [2]. Electrospinning can create a perpetual polymer nanofibre and nanofibre nonwoven [3] where the liquid polymer droplet is charged with electricity, which then creates a jet, followed by stretching and elongation to produce fibre [5]. When the physical features and chemical practicality of nanofibres emerge, it can be used in a wide variety of applications, such as air and water purification, drug (gene) delivery, wound dressing, enzyme immobilisation, tissue engineering, gas storage, and sensors and electrodes in electronics [4].

Filtration of wastewater is required because industrial wastewater usually pollutes water resources, causes environmental imbalances, and has a negative impact on human health [6]. Filtration can be defined as a process where solid substances are removed from a fluid or liquid wastewater by running through a porous medium [7]. There are different filtration modes in water treatment, such as treatment of drinking water, treatment of wastewater, water disinfection [8], or dewatering [6]. In a wastewater treatment, the use or the potential use of electrospun nanofibres for water filtration has been gaining attention as the fibres give high porosity and good functional abilities [6]. There have been many studies on water filtration using the nanofibres technology. Zander and his colleagues (2016) employed polyethylene terephthalate (PET) from discarded plastic bottles to create a water filter membrane, while reducing plastic waste [9]. Some studies focus on the ability of nanofibre membranes for specific water treatment, such as oil removal [10], dyes [11], bacteria or viruses [8], or desalination [12]. The development of novel polyvinyl fluoride (PVDF) nanofibrous multilayer membrane with further lamination was investigated by other researchers in the improvement of the filtration application either for air or water filtration [10].

There are also many studies to improve the mechanical strength and water flux of nanofibre membranes as these are the main issues related to the nanofibre membranes for water filtration. Several reviews were conducted on the fabrications and applications [17,18,19], the parameters [20,21,22], and the materials [19,23] of electrospun nanofibres. The reviews on mechanical properties of nanofibres and water flux for water filtration are vital as these properties are the main hindrance in implementing nanofibre membranes for water filtration. A high mechanical strength of the membrane for water filtration is required as the membranes have to withstand operational conditions and handling during module fabrication [14]. In addition, the requirement of high permeate flux or anti-fouling is crucial as it can reduce the energy required in water filtration [15].

2. Nanofibre as Water Filtration Membrane

Among the methods to produce nanofibres, electrospinning is a unique synthetic method that uses electrostatic forces, which produces nanofibres ranging from 40 to 200 nm in diameters [24]. Electrospinning requires five main components of apparatus, including a high voltage supply, a syringe to feed the polymer solution, a metal spinneret or a needle to transfer the polymer solution, a syringe pump to pump the polymer solution from the syringe reservoir, and a ground collector to collect the ejected polymer fibres [25]. It involves the extrusion of fibre by applying an electrical potential between a polymer droplet held at the end of the nozzle of the spinneret and the grounded collector plate [26]. Electrospinning gains its popularity due to its simple, versatile, and promising process to produce continuous nanofibres from synthetic and natural polymers [26]. Polymeric nanofibres was developed as a filtration membrane because it offers advantages, such as high porosity, low basis weight, high surface area, manageable pore size, and continuously interconnected pores [16]. These advantages have been utilized as water filtration media, which effectively remove contaminants [4] for microfiltration, ultrafiltration, and nanofiltration [16]. The nanofibre is usually layered on top of strong nonwoven polymers where the nonwoven polymer acts as a support layer to increase its mechanical properties [16]. As illustrated in Figure 1, in the ultrafiltration application, the thin film nanofibrous composite (TFNC) membrane is a three-layered membrane comprises of polyethylene terephthalate PET (bottom layer), electrospun polyacrylonitrile (PAN) nanofibre (middle support), and cellulose from ionic liquid solution (barrier) [4].

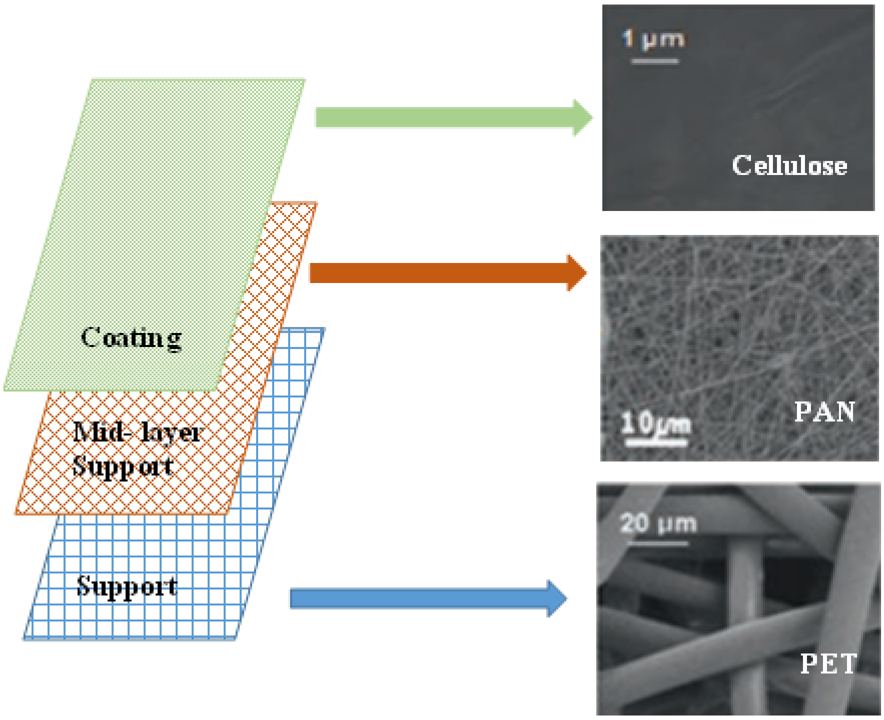

Figure 1: Hierarchical structure of cellulose based TFNC ultrafiltration membrane. Figure was adapted and modified from [4].

3. Advantages and Challenges of Nanofibre Membranes as Water Treatment Membrane

3.1. Advantages

Electrospun nanofibres have a large surface area to volume ratio, high porosity, excellent water permeability, and flexibility, which enable them to be widely applied in air filtration, water filtration, water treatment, desalination, and adsorption [2,4,13,27,28]. Electrospinning is also a practical and simple way to generate nanostructure as it is easy to control the nanofibre microstructure arrangement, diameter, and material selection [2]. Furthermore, electrospinning can increase the mechanical strength without considerably changing the morphology and dimension of the membranes [13,29]. The large surface-to-volume ratio of electrospun nanofibre is advantageous for toxins adsorption, such as viruses, dyes, and heavy metal ions if the surface to volume ratio is properly modified [4]. Electrospinning can create nanofibres with unique shapes at a low cost and with a high rate of production [30]. An addition of nanofibres to a standard micron-sized fibrous filter medium can increase the separation efficiency from 61 % to 91 % [31].

3.2. Challenges

Fouling issues from the nanofibre membranes can occur due to pore blockage, hence providing a greater filtration resistance but degrades the hydraulic performance [27,32]. In addition, nanofibre membranes have a weak mechanical strength caused by their high porosity and weak bonding at the junction of the fibres [27,33]. The poor mechanical strength is also due to its small fibre diameters, and a highly porous structure [13]. The defect-prone nature of nanofibres mat layers proves to be challenging to apply in filtration, such as wastewater treatment where the nanofibre membranes suffer from shrinkage and distortion [32]. The defects include scratching, where if under a high-pressure backwash, nanofibre membranes can be easily delaminated [27]. The insufficient mechanical strength and large pore size dispersion of nanofibre membranes are major setbacks to their use in membrane distillation [27].

4. Methods in Improving the Mechanical Properties of Nanofibre Membranes

The general definition of mechanical strength is the ability to withstand the stress of physical forces. The mechanical qualities of membrane systems must be improved for a filtration process to be commercialised successfully [33]. To endure operational circumstances, pressure-driven membrane filtering technologies require an appropriate mechanical strength [33,34]. There are many ways to increase mechanical properties of nanofibre mebranes, such as post treatment, which include solvent vapour [27, 29, 35, 36], chemical crosslinking [14.45], hot pressing, annealing [31,48,49,50,51,52,53], hot stretching, and stretching/drawing (Figure 2).

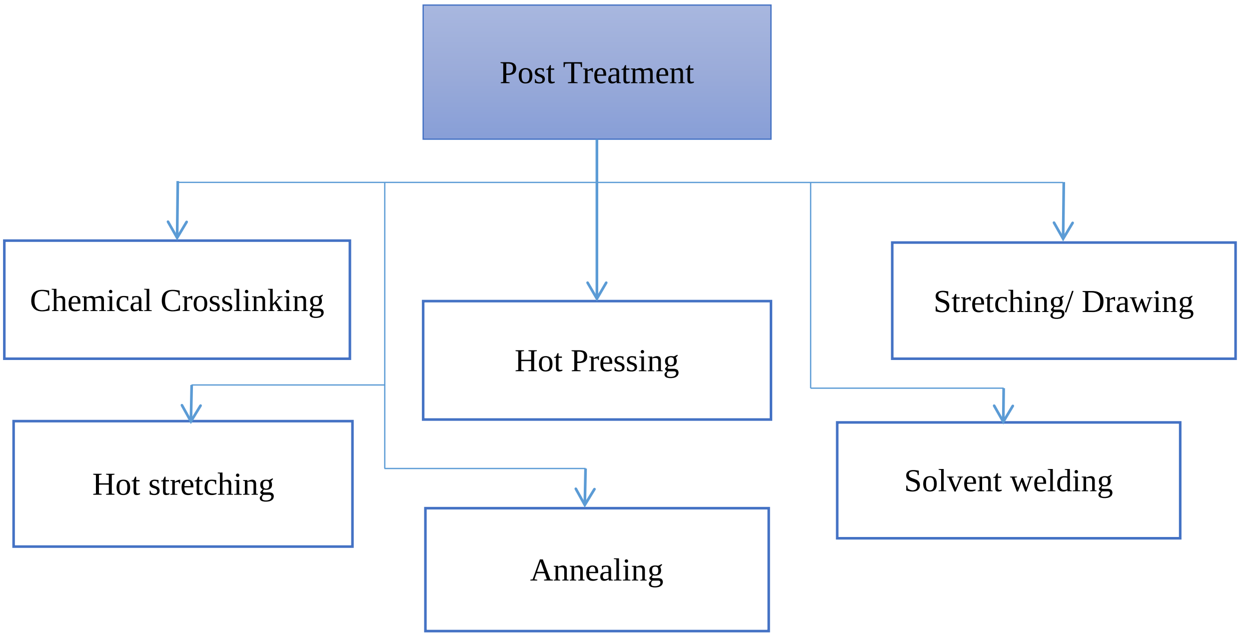

Figure 2: Post treatment methods to increase the mechanical strength of nanofibre membrane

The treatment of nanofibre membranes using solvent vapour is preferable as the nanoscale phase separation is more organised and it has a better thermodynamic stable morphology of the active layer [27,36]. This treatment is also able to promote the physical fusion between the fibres at the fibre junction and gives a smoother surface, which controls the fouling rate, and hence increases the nanofibre membrane's strength [27]. The treatment of solvent vapour is used for different reasons, such as for generating attoliter reactors, welding nanofibre mats into conductive films, introducing secondary nanostructure onto/into electrospun fibres, and infiltrating the channels in a porous template with polymeric materials [29]. As reported by A. Rianjanu et al. (2018), the nanofibre mat is cut into sizable coupons and placed on a petri dish. The petri dish was then placed on top of the beaker where the nanofibre mat was facing inside the beaker. The amount of solution used varied according to the requirement [35]. During this process, nanofibrous samples are directly exposed to solvent vapours to fuse fibres at their junction points [37]. The schematic diagram of the solvent vapour process is shown in Figure 3. Another study treated a nanofibre mat with a well-controlled method by the partial pressure of solvent to fuse electrospun nanofibre made of both semi-crystalline and amorphous polymers [29].

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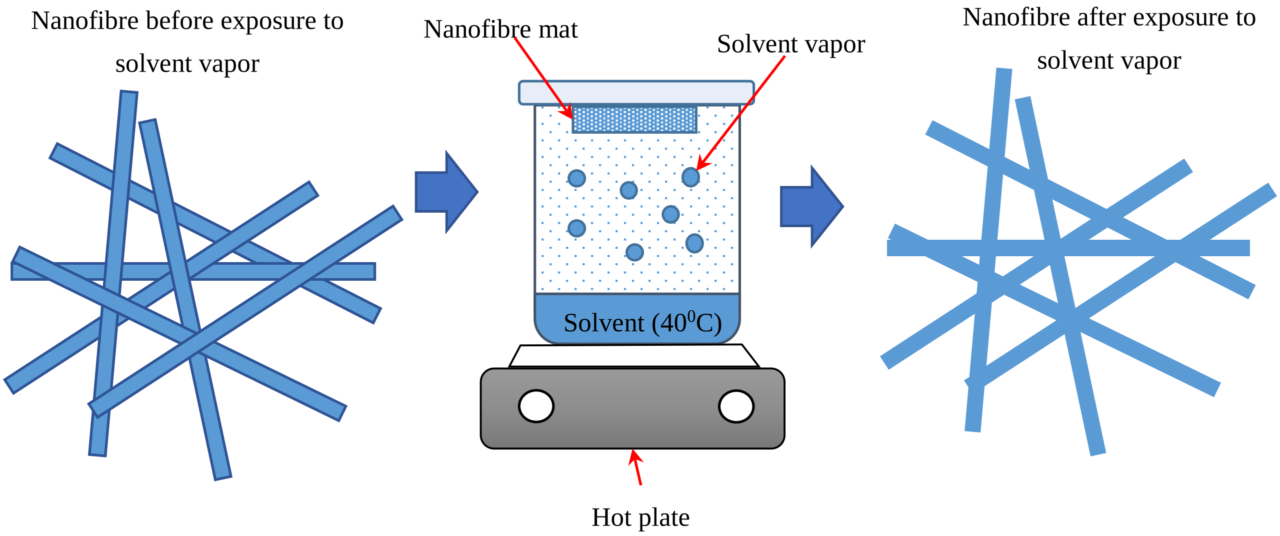

Figure 3: Schematic illustration of solvent vapour process. (Adapted and modified from [29,36])

Another way of improving the mechanical properties of electrospun fibrous membranes is to heat treat the membranes as illustrated in Figure 4 [38]. Due to the rearrangement of polymer chains at higher temperatures, heat treatment or annealing of these membranes/fibrous webs improves crystallinity [38,39]. It is also said to be a simple and environmentally friendly treatment as the use of dangerous chemical substances can be avoided [40]. Furthermore, a partial fibre fusion can occur, resulting in inter-fibre welding at fibre crossover locations, giving these membranes a structural integrity [38,41]. It was proposed that annealing should be done above the crystallisation temperature and below the melting point of the polymer for best results and to avoid a full melting of the fibrous membrane [38]. Heat treatment in these settings improves crystallinity by rearranging molecular chains in amorphous regions, as well as inter fibre fusion due to partial melting of fibres at junction points [38]. The mechanical characteristics of electrospun fibrous membranes are often improved by these two aspects, namely, increased crystallinity and fibre welding at crossing locations [38,42]. For the construction of an ideal composite structure, a proper combination of heating rate, temperature, and time for the thermal treatment are crucial, ensuring a superior cycle performance and a higher rate of discharge capability [43]. Nonetheless, some studies state that heat treatment may lower the diameter of the fibres and the pore size of the membrane [39].

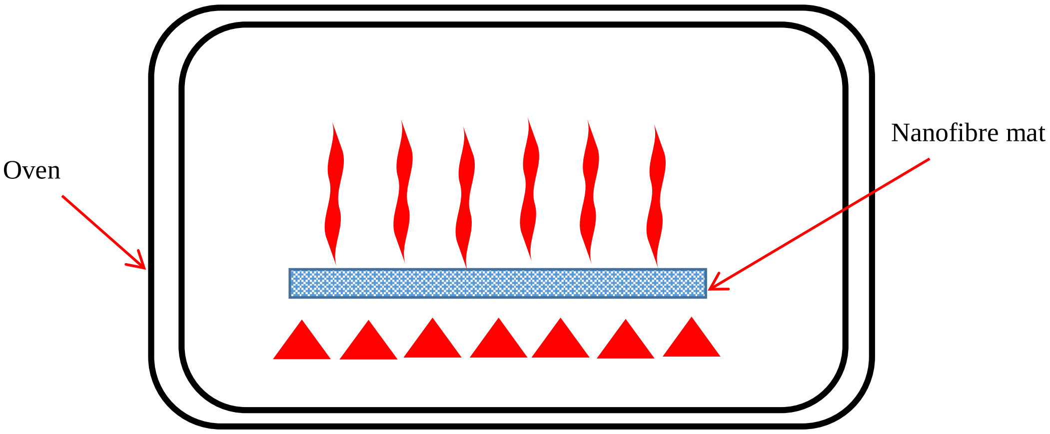

Figure 4: Schematic illustration of thermal treatment on nanofiber. (Adapted and modified from [42])

Chemical reactions, such as cross-linking, can also be used to improve fibre–fibre bonding [44]. Hydrophilic ENMs commonly use this strategy to increase their water integrity [44]. Covalent bonds are generated between the molecular chains of a polymer through chemical crosslinking, increasing its molecular weight and improving mechanical qualities, such as strength, stiffness, abrasion resistance, hardness, and thermal stability, among others [38]. The chemical structure of the reactants involved, as well as their concentration, determines the kinetics of a crosslinking reaction [38]. As a result, the crosslink density and rate of reaction can be adjusted by adjusting the crosslinker concentration and reaction conditions [38]. Another research states that chemical measurement can improve bonding at junction points in the nanofibre membrane by welding or soldering the nanofibre membrane together, as well as changing the degree of molecular orientation of the polymer, which is thought to have a significant impact on the nanofibre's mechanical properties [45]. Using a proper crosslinker, similar crosslinking procedures can be used to establish inter-fibre linkages in electrospun membranes [38]. Methods to improve the mechanical properties of electropsun nanofibres have been well reported by previous studies. However, the effectiveness of these methods to enhance the mechanical properties and flux of the electrospun membrane are yet understood. Hence, this review paper highlights the methods improving mechanical strength, such as through solvent vapour treatment, heat treatment, and chemical crosslinking. This review also highlights the effect of these treatments on water flux since water flux is vital in water filtration. By increasing the mechanical strength and water flux, nanofibre membrane then can be applied on water filtration for future perspective.

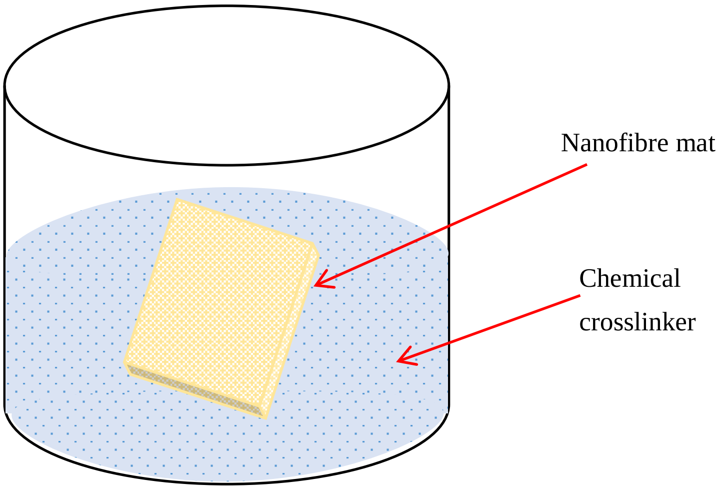

Figure 5: Schematic illustration of chemical crosslinking on a nanofiber mat. The figure was adapted and modified from [45].

5.1 The Mechanical Properties of Nanofibre Membrane after Solvent Vapour Treatment

As reported by Abd Halim et al. (2019), the solvent vapour method was conducted by using formic acid. The electrospun Nylon 6,6 was treated at different treatment periods from 5, 12, 24, and 48 hours at room temperature [27]. It was reported that the tensile strength of the nylon 6,6 nanofibre mat after treatment increased with exposure time. The tensile strength increased tremendously by 91 % upon exposure of 24 hours compared to untreated samples. The increase of mechanical strength was caused by the condensation of formic acid. On the other hand, the increment of tensile strength with the exposure time was due to the higher number of fibre fusion between the fibre junctions. In addition, the solvent vapour treatment promoted random fusing across the nanofibre mat. Random fusing resulted in a greater tensile strength distribution, therefore, boosting the nanofibre mat's tensile strength. It also expanded the fibres by combining them at different locations. This correlates with FESEM images of the untreated membrane with the treated membranes of different exposure times. Meanwhile, overexposure to solvent vapour damages the nanofibre mat, hence lowering its mechanical strength. When the exposure duration was set to 48 hours, the tensile strength diminished. Uncontrolled swelling caused fusion between fibre layers as a result of an excessive exposure to solvent vapour. As a result, the tensile strength distribution among fibres was narrow.

Another study conducted by Huang and his colleagues used two different methods for solvent vapour. In method A, the nanofibres were left on an aluminium foil, while in method B, the nanofibres were removed from the foil. Two types of polymeric electrospun membrane were tested, including electrospun Polyacrylonitrile (PAN) and Polysulfone (PSU), both using N, N Dimethylformamide (DMF) for the solvent treatment [13]. The study found the tensile strength and modulus of PAN using method A. However, with method B, there was only a small increase in both tensile strength and Young's modulus (56 % and 25 %, respectively). The results for PSu membrane corresponded with the results of PAN membrane where both tensile strength and Young's modulus increased to 400 %. In method B, the tensile strength and Young's modulus of the membranes were increased by 80 % and 110 %, respectively. The mechanical property results are consistent with the SEM data, indicating that solvent-induced fusion at the fibre junction areas was responsible for the abrupt rise in modulus and tensile properties in PAN and PSu membranes. In other words, the post-treatment condensation of DMF vapour could maintain the electrospun mat relatively "wet", resulting in a fusion between the inter-fiber connections. The swelling of the fibres may also aid in increasing the strength of the membranes. Method B-treated membranes are projected to have less fusion and swelling; therefore, the mechanical properties are unlikely to increase significantly. It is also worth noting that the swelling effect may diminish when the ENMs are submerged because DMF diffuses are out of the fibres, while fibre–fibre fusion does not.

The use of solvent vapour to treat electrospun membrane was also investigated by other studies [29,35,37,38,47]. The solvent used in these studies varied from formic acid, acetone, methanol, N,N dimethylformamide (DMF), dichloromethane (DCM) dimethyl sulfoxide (DMSO), and dimethylacetamide (DMAc). The studies show improvement of tensile strength of treated nanofibre membranes. Furthermore, the improvement of tensile strength is related to exposure time where, as the exposure time increases, the tensile strength increases [29,35,37,38,47]. This correlates to a higher number of fibre fusion between fibre junction points in both the in-plane and normal-to-plane directions, preventing mat de-lamination [29,35,37,38,47]. However, overexposure to solvent vapour will damage the fibre structure, thus decreasing the tensile strength and at a certain point, the membrane becomes slightly transparent [35]. This is due to an excessive fibre fusion [27,35]. Therefore, the determination of exposure time is critical in improving the tensile strength, while preventing damage to the nanofibre membrane.

To sum up, solvent vapour treatment can increase the tensile strength of nanofibre membranes as it fuses the fibre joints. This makes nanofibre membranes to be potentially used in the water filtration sector as the treatment may prevent delamination, shrinkage, and distortion if under a high-pressure backwash.

5.2 The Effects of Solvent Vapour Treatment to the Water Flux

High permeate flux or anti-fouling requirements are important because they can lower the amount of energy used in water filtration [26]. Therefore, it is essential to access the filtration properties, such as water permeability of the nanofibre membrane. A study was done by N.S. Halim et al. (2018) on the effects of solvent vapour treatment on electrospun nylon 6,6 nanofibre membrane. The nylon 6,6 EMs was exposed to formic acid vapour at various durations (5, 12, 24, and 48 hours) at room temperature. The results show that the steady-state pure water permeability of the treated for 5 hours is 1 % lower than the untreated membrane. However, if the membrane was treated for 48 hours the water permeability decreases to 44 % compared to the untreated membrane. This relates to the effect of pore size on the exposure time. As the treatment time increases, the pore size increases, hence a decrease in water permeability. To induce fusion fibres at the contacting locations, a shorter period is preferred. Only a small portion of the nanofibre surfaces dissolves, just enough to create physical crosslinks between the fibres. Membrane porosity and permeability will not be affected as a result of this, and membrane fibres will be strengthened through crosslinking. Therefore, the membrane should be exposed at 5 hours to prevent the reduction of porosity and water permeability.

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Another study was done by C. Liu et al. (2016) on solvent vapour treatment to Cellulose acetate/Polyvinylidenefluoride (CA/PVDF) ENMs. In this research, it is shown that the membrane M1 (untreated nanofibre membrane) has the highest water flux, which is (17.4m3/m2.hr). On the other hand, M5 (treated condition: solvent of acetone 500C for 10 minutes) had a lower flux of 0.12m3/m2.h than of M1. In comparison, M5 decreased its water flux to 0.7 % compared to M1. Despite M5 having a lower flux than M1, the rejection rate of M5 (99.99 %) is much higher than M1 (44.4 %). This is due to the difference in pore size as M1 (largest pore diameter: 1.93 micrometre) had a bigger pore size than M5 (largest pore diameter 0.74 micrometre). The closest reading of water flux to untreated nanofibre membrane is M2 (6.91 m3/m2.h). When compared to the untreated M2, the size is 39.7 % lower than M1, while having a good rejection to the emulsion. The decline in water flux is mostly due to the membrane's pore size and porosity, which were found to be consistent with the SEM data. The solvent vapour treatment enables a significant increase in membrane integrity without sacrificing the pore size and porosity of the resultant membranes, which is a desired property for filtration applications.

Altogether, the solvent vapour treatment causes the water permeability of the nanofibre membrane to decrease slightly. This is agreeable with other studies [8,27,35,47] where exposure to solvent vapour causes a decrease in pore size, which reduces the porosity and permeability [27]. Others claim that due to a better fibre bonding caused by solvent vapour treatment, the ENMs increase their resistance to compression, and therefore, permeability drops [8,27,35,47]. Even though solvent vapour treatment reduces permeability, it also reduces fouling, which extends the membrane life and lowers membrane operating expenses. In general, the solvent vapour treatment had little effect on ENMs’ flux performance, particularly when evaluated at greater hydraulic pressures. In addition, the solvent vapour treatment enables a significant increase in membrane integrity without sacrificing the pore size and porosity of the resultant membranes, which is a desired property for filtration applications.

6.1 The Mechanical Properties of Nanofibre Membrane after Heat Treatment

Heat treatment is one of the common treatments applied on the electrospun membrane. Y. Wang et al. (2019) heat treated Polyphenylsufone (PPSU) electrospun nanofibe membrane (ENMs) in an oven at 2400 C for 1 hour [48]. To prevent shrinkage, the sidewalls of the membranes were sealed during the heat treatment. The heat-treated membranes had dramatically improved tensile characteristics as compared to untreated membranes. The elastic modulus and the breaking stress increased to 930 % and 853 % higher than that of the untreated membranes. The loose structure and poor cohesiveness of the untreated PPSU membrane are due to the fibres not binding with each other. Polymer fibres were fused at the intersections during the heating process to generate a more compact and integrated structure. Furthermore, during the heat treatment, the segmental movements of the polymer chains effectively eliminated the internal stress created during the spinning process, resulting in improved structural stability. Furthermore, by anchoring the sidewalls of the membranes, segmental motions were able to rearrange the polymer chains along the direction of the external force applied, increasing the orientation degree of the amorphous polymer. All these factors aided in the improvement of structural stability and mechanical qualities.

Another study was done by S. Himaeigohal et al. (2012). In this study, the blended PSU/PAN membrane was heat-treated for 5 hours at 1850 C. The results show that heat-treated membrane can withstand substantially higher levels of stress than untreated membrane. The treated membrane could withstand 2.507 N/mm2, whereas the untreated membrane could only withstand 1.266 N/mm2 until it ruptured. This shows an increase of 198 % of tensile strength. Heat-treated membranes, on the other hand, had a lower strain level of around 5.927 % than untreated membranes, which have a strain of about 7.854 % before rupture. These findings show that heat treatment improves membrane durability when compared to that of untreated membranes. Lower strain indicates less plasticity and a more rigid structure. In addition, untreated membranes scattered and tore during wastewater filtering, but heat-treated membranes remained intact. As a result of the heat treatment, the mechanical qualities have improved.

Heat treatment was also investigated in other studies [31, 49,50, 51,53]. Although heat treatment was seen to increase tensile strength in all of these studies [31, 49,50, 51,53], some studies show a decrease in elongation at break [50,51,52,53]. The tensile strength was increased due to the fibre fusing with one another. Meanwhile, the thickened fibres and a greater degree of crystallinity increase the stiffness of the single fibres, while decreasing their ductility. Therefore, thermal treatment is able to increase the tensile strength, while effecting the stiffness or elongation at break.

6.2 The Effects of Heat Treatment to the Water Flux

Heat treatment has a great impact on water permeability of ENMs whereas a study by B. Ozbey-Unal et al. (2020) shows an increase in permeate flux and salt rejection of Polyvinylide fluoride (PVDF) ENMs. The duration of heat treatment was for 1 hour with a temperature of 1000 C. The permeate flux and salt rejection values were increased from 26.4 kg/m2 h to 30.4 kg/m2 h and 94.9 % to 95.5 %, respectively, after heat treatment. The water flux was 115 % higher when compared to that of the untreated water. When the heat treatment was conducted, the thickness of the membrane was reduced from 196.2 (+/-)9.8 micrometre to 188.4 (+/-) 6.2 micrometre, resulting in a shorter total vapour transfer distance and a reduction in mass transfer resistance.

Another study shows that in addition to an increase in the membrane’s structural integrity and mechanical strength, the pure water flux also increases [49]. In this study, Polyphenylsufone (PPSU) ENMs were treated for 1 hour at 2450 C. The heat-treated membrane's structural integrity and increased mechanical strength, as demonstrated by SEM pictures and a tensile test, resulted in lesser compaction, and hence higher porosity during filtration. This property, combined with the heat-treated membrane's bigger pore radius compared to that of the untreated one, resulted in a 144 % higher pure water flux. The rejection values for both treated and untreated membranes were nearly identical. The untreated and heat-treated membranes, both obtained 100 % turbidity rejection, implying that the wastewater suspended particles were properly removed.

Meanwhile, other studies show a decrease in water flux after ENMs were heat-treated [51,52,53]. L. Li et al. (2013) state that heat treatment causes the pore size and porosity to decrease causing a lower initial flux compared to that of the untreated ENMs. They also state that the pores of the heat-treated membranes were more resistant to liquid flow than the pores of the untreated membranes, and easier to be blocked by the filtered particles due to their smaller pore size and porosity, resulting in a faster formation of a filter cake, but also increased particle rejection. This statement is agreeable with another study [53] where they state that the heat-treated membrane also showed a considerably superior retention efficiency for the colloidal nanoparticles, despite having a lower permeability due to the densed cake layer development, which is due to a lower disintegration propensity before the highest applied feed pressure, i.e., 2 bar.

To sum up, water flux is highly impacted by pore size and porosity caused by the treatment. If pore size and porosity increase, the water flux increases. Therefore, it is vital to determine the heat treatment temperature that does not greatly decrease pore size and porosity.

7.1 The Mechanical Properties of Nanofibre Membrane After Chemical Crosslinking

A study shows that Polydopamine (PDA) modification improves the mechanical characteristics of both Polyacrylonitrile (PAN) and Polysufone (PSu) membranes [14]. The ENMs membranes were coated with PDA and tris-HCl with treatment periods of 1 and 18 hours at room temperature. The result shows that PAN EMNs had a 100 % increase in tensile strength and Young's modulus following alteration, signifying a stronger and stiffer material. The ultimate tensile strength and Young's modulus enhancement for PSu ENMs were found to be 80 % and 210 %, respectively, for PSu ENMs. However, for both PAN and PSu, there is no statistically significant change in elongation at break following alteration, indicating that nanofiber flexibility was preserved. Since the PDA layer binds nanofibers together, promoting interconnectivity within the mat, the PDA coated ENMs demonstrated increased mechanical characteristics. The fibres were glued together at places of overlap when the PDA layer formed in the blank space between them. When comparing the mechanical qualities of PAN and PSu after 18 hours of modification against 1 hour of coating time, there was essentially no improvement in mechanical properties. A mechanical strength test demonstrates that extending the coating period does not improve the strength and is, therefore, less time and cost-effective.

Another study was conducted by J. Chai et al. (2016) using solvent with varied ethanol/acetone volume ratios for the post-treatment of Bamboo cellulose (B-CA) ENMs. The results show that the strength and modulus of the treated B-CA membranes with 95/5 (volume/volume) ethanol/acetone mixture solutions increased dramatically. The mechanical property of the nanofibres deteriorated as the acetone ratio in the solution was increased further. When compared to the untreated sample, the treated membrane increased to 203 %. The increase in tensile property and modulus in B-CA membranes might be attributable to increased fibre density and solvent-induced fusion at the fibre junction locations, according to the mechanical property data. In other words, the little amount of acetone in the post-treatment mixed solution could keep the electrospun membrane relatively "wet" and "swollen," resulting in an inter-fibre fusion.

Chemical crosslinking can increase the mechanical strength of nanofibre without effecting its flexibility. The improvement of mechanical strength is due to fusion of fibre via solvent. The solvent causes the fibres to become relatively wet and swollen. Determining the soaking time is crucial as after the optimal period of soaking time, there will be no improvement on the mechanical strength.

7.2 The Effects of Chemical Crosslinking to the Water Flux

Although chemical crosslinking increases mechanical properties of ENMs, it reduces water permeability of ENMs. L. Huang et al. (2014) state that with increasing applied pressure, the pure water permeability of all three membranes (PAN pre-wet, PAN dry, and PAN– PDA 1-hour ENMs) declined. This is due to the applied pressure compacting the membrane. There is no permeability enhancement for the PAN–PDA 1-hour ENMs as compared to that of the dry unmodified PAN ENMs. Instead, there was a modest drop in permeability (down to 96 %) when compared to that of the unmodified ENMs, which is likely attributable to the coated samples' reduced pore volume and pore widths. Nonetheless, for the PAN–PDA 1 h ENMs, the pore shape had a minor impact on the water flux performance, and ENMs retained their high permeability. The pure water permeability of all three membranes (pre-wet PSu, dry PSu, and PSu– PDA 1 h ENMs) declined with increasing applied pressure, similar to that of the PAN ENMs. The PSu–PDA 1 h ENMs, like the pre-wet PSu ENMs, had a greater flux than that of the dry PSu ENMs. The flux of the PSU-PDA 1h increased by 118 percent as compared to that of the dry PSu ENMs. This is because the PDA alteration improves surface hydrophilicity, while also potentially block smaller pores. The improved surface wettability of the PSu–PDA 1 h ENMs overcomes the effect of reduced pore volume and pore diameters. The flux performance of the PSu–PDA 1 h ENMs was similar to that of the pre-wet PSu ENMs.

J. Chai et al. (2016) are also in agreeable with L. Huang et al. (2014) where in their study, after solvent-soaking treatments, the pure water permeability of B-CA ENMs dropped somewhat under the same applied pressure. When compared to the untreated membrane, the treated membrane decreased to 89.9 %. This could be because the solvent-soaking procedure caused a fibre cross-bonding and fibre deformation in the ENM, which reduced porosity and porosity interconnectivity (raising tortuosity) by clogging pores. The pore size was also lowered as a result of the blockage. The solvent-soaking treatment did not significantly reduce the B-CA ENMs' pure water permeability, while dramatically increasing their mechanical strength, making them ideal for water filtering applications. Altogether, chemical crosslinking reduces the water permeability as it reduces the pore size and porosity although it can improve surface wettability and membrane mechanical strength.

8. Summary and Future perspective

To summarise, all the post treatments stated above were able to improve the mechanical characteristics of nanofibre membranes by random fusing across the membranes, with the vapour condensation during the post-treatment resulting in a fusion between inter–fibre contacts in the mats. It resulted in a wider tensile strength distribution, increasing the tensile strength of nanofibre mats. It also stretched the fibres by joining them in various places. Meanwhile, an excessive solvent vapour exposure weakened the nanofibre mat's mechanical strength. As a result of an excessive exposure to solvent vapour, uncontrolled swelling produced a fusion between fibre layers. In effect, the distribution of tensile strength among fibres became limited. Mechanically, it was quite strong. Although the mechanical strength of nanofibres was increased by solvent vapour, the water flux was reduced. The drop in water permeability with exposure time was caused by a reduction in pore size, which lowered the membrane's porosity and permeability. This finding is also agreeable with other post treatments (heat treatment and chemical crosslinking) as when the post treatment can cause reduction in pores size and porosity, water flux also reduces. However, this is not the case for some heat treatment studies, as some studies show a shorter total vapour transfer distance and a reduction in mass transfer resistance as heat treatment reduces the thickness. When comparing all three post treatments, the solvent soaking treatment reduced slightly on water permeability (reduce by 0.7 to 15 %), while having a great mechanical strength. Others decreased water permeability by 152 %. Nonetheless, an increase in water permeability was seen in some of the heat treatments.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, SSMH, NDNA, AFM, AMH, MKA, MRA; methodology, SSMH, NDNA; software, SSMH, NDNA; validation, SSMH, NDNA; formal analysis, AFM, AMH; investigation, SSMH, NDNA; resources, AFM, AMH; data curation, SSMH, NDNA.; writing—original draft preparation, SSMH, NDNA, AFM, AMH, MKA, MRA; writing—review and editing, SSMH, NDNA, AFM, AMH, MKA, MRA; visualization, NDNA; supervision, NDNA; project administration, SSMH, NDNA; funding acquisition, NDNA, AMH. All authors have read and agreed to the published version of the manuscript."

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