Solvent vapor treatment improves mechanical strength of electrospun polyvinyl alcohol nanofibers

Abstract

Electrospun nanofibers of polyvinyl alcohol (PVA) have poor mechanical strength. As such their use has often been avoided, particularly in applications that require high mechanical properties. The objective of this study is to increase the mechanical properties of PVA nanofiber mats via physical crosslinking with solvent vapor treatment using organic solvents, dimethyl sulfoxide (DMSO), N, N-dimethyl formamide (DMF), and methanol. The effect of solvent vapor treatment on PVA nanofibers is clearly observed by scanning electron microscope (SEM). The tensile strength increased by over 60%, 90%, and 115% after solvent vapor treatment with DMF at a temperature of 40 °C for 2 h, 4 h, and 8 h, respectively, compared to untreated PVA nanofibers. In addition, Young’s modulus of PVA nanofiber mats also increased after DMF treatment. As a comparison, DMSO and methanol were also used in solvent vapor treatment because of differences in their polymer-solvent affinity. Results showed that the highest improvement (100%) in mechanical strength was obtained using DMF. This study shows that solvent vapor treatment offers a simple and inexpensive method that provides
excellent results and is a promising alternative treatment for use in increasing the mechanical properties of electrospun nanofibers.

Keywords: Engineering, Materials science, Nanotechnology

1. Introduction

Electrospinning is a simple, reproducible, continuous, versatile, and efficient process used to fabricate long nanofibers on a large scale using a rich variety of materials. Recent studies have focused on using this technique for various applications, such as with affinity membranes, for drug release, tissue scaffolds, sensors, as protective clothing agents, and in the fields of energy, electronic devices, and composite reinforcement [1, 2, 3, 4, 5, 6], mainly because of the remarkable properties of electrospun nanofibers, such as a small diameter, high aspect ratio, large specific surface area, and unique physical and chemical properties [7]. The polymers commonly used for fabricating the electrospun nanofiber membrane are polyvinylidene fluoride (PVDF) [8], polysulfone (PSU) [9], polyacrylonitrile (PAN) [10], polyethersulfone [11], polyamide (PA) [12], and polyvinyl alcohol (PVA) [13, 14, 15, 16].

However, although they have such remarkable properties, the use of nanofiber membranes in various applications has often been avoided due to their poor mechanical properties. Many methods have been developed to increase the mechanical strength of nanofiber mats, including changing non-woven fiber mats into self-bundled fiber yarns [17] and reinforcing single nanofibers with other materials [18, 19, 20, 21], but these methods have been complex and costly. However, one approach is enhancing at junction points in the nanofiber mats by crosslinking fibers together [22, 23], and this can be achieved in three ways: first, the mat is heated to a temperature between its glass transition and melting temperature [24, 25]; second, the mat is treated with glutaraldehyde (GA) [26, 27, 28], and third, solvent vapor treatment is applied [29, 30, 31].

Recent studies have shown that solvent vapor treatment can enhance the mechanical strength of nanofiber mats without significantly changing the membrane morphology or dimensions. The solvent plays a crucial role in determining the mechanical properties of the mats [29]. In this respect, Huang et al. (2013) used solvent vapor treatment with N,N-dimethyl formamide (DMF) to improve the mechanical strength of polyacrylonitrile (PAN) and PSU nanofiber mats; results showed increases of 300% and 110% in the tensile strengths of PAN and PSU nanofiber mats, respectively [29]. In addition, 2016 Liu et al. (2016) used acetone/N,N-dimethylacetamide (acetone/DMAc) solvent with cellulose acetate/polyvinylidene fluoride (CA/PVDF) nanofibers to perform physical cross-links [30], and Huang et al. (2016) used solvent vapor treatment with formic acid on PAN/Ag nanofibers to control the radial structural gradient [31].
Another effect of solvent vapor treatment is to improve the electrical conductivity of the thin-film; this process is known as polar solvent vapor annealing (PVSA) treatment [32]. The most commonly used solvents in PVSA treatment include dimethyl sulfoxide (DMSO), ethylene glycol (EG), N-methyl-2-pyrrolidone (NMP), N,N-dimethyl formamide (DMF), and methanol [33, 34]. In this paper, the effect of certain different solvents commonly used in PVSA are investigated, with the aim of improving the mechanical strength of PVA nanofiber mats. Morphological, thermal, and mechanical analyzes are conducted on PVA nanofibers after solvent vapor treatment.

2. Materials and methods

2.1. Materials

Polyvinyl alcohol (PVA) (M_w = 89,000–98,000, 99% hydrolysis) obtained from Sigma–Aldrich was used to prepare nanofibers. Solvents used for vapor treatment include dimethyl sulfoxide (DMSO), N, N-dimethyl formamide (DMF), and methanol, which were purchased from Merck, Germany. All materials were used as received without conducting any further purification processes.

2.2. Electrospinning nanofiber

Polyvinyl alcohol (PVA) solution was prepared by dissolving 8 wt%–15 wt% PVA polymer in distilled water and stirring for 1–2 h at a temperature of 90 ºC to obtain an homogeneous solution. Each solution was then transferred into a 10 mL syringe to conduct the electrospinning process, during which a DC voltage of 10 kV was applied and the tip to collector distance was set as 8 cm; the collector used in the electrospinning process was a metal plate covered with aluminum foil. The electrospinning process was conducted for 2 h to obtain a suitable nanofiber mat thickness. Finally, mats were placed in a drying chamber for 24 h to evaporate residual solvent prior to further treatment.

2.3. Solvent vapor treatment

A schematic diagram illustrating the solvent vapor treatment used in this study is shown in Fig. 1. Following the electrospinning process, the nanofiber mats were then cut into smaller coupons (measuring approximately 12 cm × 3 cm) and placed on the top of a petri dish (D = 12 cm). The amount of solvent used was 1.25 mL, 2.50 mL, and 5.00 mL at evaporation times of 2 h, 4 h, and 8 h, respectively; the solvent was then evaporated with a hot plate stirrer at a temperature set at 40 ºC. After treatment; all samples were dried in a drying chamber for 24 h to remove all solvent residual before further characterization.
2.4. Sample characterization

2.4.1. Scanning electron microscope (SEM)

The nanofiber morphology of samples, both as-spun and after solvent vapor treatment, was analyzed using SEM JEOL JSM–6510. The samples were mounted on metal stubs and sputter-coated with platinum for 70–90 s with a JEOL JEC–3000FC auto fine coater. The average nanofiber diameter and standard deviation were determined by measuring the diameters of approximately 100 fibers using ImageJ software.

2.4.2. Mechanical properties

The mechanical properties of all the PVA nanofiber mats were measured before and after solvent vapor treatment using a universal testing machine (Zwick Z0.5) with a ASTM D822 standard. The mats (both before and after solvent vapor treatment) were cut into smaller coupons measuring approximately 12 cm × 4 cm for use in conducting mechanical tests. A minimum of three strips with lengths of 12 cm × 4 cm were cut from each type of sample to conduct mechanic measurements with a tensile rate set at approximately 10 mm/min.

2.4.3. Thermal analysis

Changes in the thermal behavior of PVA nanofiber mats as a result of the crosslinking process were observed by differential scanning calorimetry (DSC) using a DSC–60 plus Shimadzu. For the crystallinity measurements, mats were scanned at a heating rate of 10 °C/min from 50–300 °C, and a sample mass of ~2.0 mg was used in each experiment. The percentage of crystallinity was calculated from the heat fusion scan using Eq. (1) as
\[\%\text{crystallinity} = \frac{\Delta H_f}{\Delta H_0} \times 100\% \]  

where \(\Delta H_f\) is enthalpy associated with melting PVA, and \(\Delta H_0\) is enthalpy of melting 100% crystalline PVA, which is reported in literature as 138.6 J/g [35].

Thermal decomposition of the nanofiber mats was observed using thermogravimetric/differential thermal analysis (TG/DTA) with a DTA60 from Shimadzu, with an N₂ atmosphere (flow rate = 20 ml/min) in a temperature range of 50–600 °C. A heating rate of 10 °C/min and a sample mass of ~2.0 mg were used in each experiment.

3. Results and discussion

3.1. Nanofiber morphology

Fig. 2 shows SEM images of PVA nanofiber mats formed using the electrospinning technique with various solution concentrations. Beaded nanofibers are clearly visible in the images with a solution concentration of 8 wt%–10 wt%; solutions with low concentrations tend to form rough (beaded) nanofibers. It is commonly known that polymer solutions with lower concentrations result in solutions with lower viscosities, and it is common to find beads along nanofiber mats with low viscosities. When the viscosity of a solution increases, a gradual change occurs in the shape of the nanofiber from one that is beaded to one that is smooth, as shown in Fig. 2. In this study, the effect of increased viscosity on nanofiber morphology is in agreement with results from other literature [36]; when the viscosity increases, the diameter of the nanofiber also increases, as shown in Table 1. This effect is probably caused by the solution having a greater resistance to being stretched by the charges on the jet [36]. As the viscosity increases, the polymer chain entanglement within the solution is increased, which maintains the continuity of the electrospinning jet during the process. In addition, when the viscosity increases, the charge on the electrospinning jet can fully stretch the solution with solvent molecules distributed among the polymer chains, which thus increases the nanofiber diameter. A smooth (without beads) and continuous nanofiber with a relatively homogenous nanofiber diameter begins to emerge at a solution concentration of 11 wt%–15 wt%.

Table 1 also shows that the deposition area decreases as the concentration increases. Increased concentration means that the viscosity of the solution is strong enough to discourage bending instability to set in for a long distance as it emerges from the tip of the needle; the jet path is then reduced and bending instability spreads over a smaller area. This reduced jet path also means less stretching of the solution, thereby resulting in fibers with larger diameters [36]. From the nanofiber results shown in Fig. 2 and Table 1, the authors decided to use a solution concentration of 12 wt%
Fig. 2. SEM image of PVA nanofibers at various PVA concentrations.
Table 1. Summary of nanofiber formation with various concentrations of PVA solutions and electrospinning parameters of 10 kV, 8 cm, and 2 h.

| Concentration (wt%) | Nanofiber Form | Deposition Area (cm²) | Nanofiber Diameter (nm) |
|---------------------|----------------|-----------------------|-------------------------|
| 8                   | More beaded    | Large                 | 90 ± 20                 |
| 9                   | Beaded         | Large                 | 111 ± 28                |
| 10                  | Beaded         | Large                 | 130 ± 37                |
| 11                  | Un-beaded      | Medium                | 225 ± 34                |
| 12                  | Un-beaded      | Medium                | 258 ± 34                |
| 13                  | Un-beaded      | Small                 | 261 ± 36                |
| 14                  | Un-beaded      | Small                 | 306 ± 40                |
| 15                  | Un-beaded      | Small                 | 344 ± 35                |

*a Based on area of collector plate ~400 cm² (large = 200–400 cm², medium = 100–200 cm², small = <100 cm²).

for further study with nanofibers, based on the larger diameter and broader deposition area achieved than with other concentrations.

3.2. Effect of solvent vapor treatment

3.2.1. Effect of treatment time

The morphologies of PVA nanofiber mats after treatment with various solvents and treatment times are shown in Fig. 3. The results indicate that changes in the...
morphology and conformation occur after solvent vapor treatment, and change to the morphology of PVA nano fiber mats begins when the mats are exposed to all solvents for 2 h. The most significant morphological changes are clearly observed in the SEM image of PVA nano fiber mats after exposure to solvent vapor for 8 h, especially for DMF and DMSO treatments. These phenomena occur due to massive swelling of the PVA nano fiber caused by the high polymer-solvent affinity and the vapor amount absorbed to the PVA nano fiber (this relationship is explained in greater detail in the discussion section). Another event clearly observed is that the nanofiber appears to form physical bonding and fusion at junction points (cross-links); this phenomenon occurs because the solvent can condense at these junctions and slightly dissolves the polymer to facilitate fusion.

The increase in exposure time affects the amount of vapor that can condense at the nanofiber junction point; this amount condenses and fuses at nanofibers junctions in relation to an increase in both tensile strength and Young’s modulus. The thickness of mats was also found to decrease after solvent vapor treatment: a thickness of approximately 100–200 μm prior to solvent vapor treatment and below 100 μm following treatment. This decrease in nanofiber thickness is due to the increasing density of the nanofiber mats in relation to nanofibers fusing at the junction points. Furthermore, the nanofiber mats were also seen to shrink slightly after vapor treatment, and this effect was most often observed with nanofibers at an evaporation time of 8 h, when the nanofibers shrunk by approximately 20% compared to untreated nanofiber mats. It was also evident that nanofibers fused together at junction points.

The tensile strength and Young’s modulus of PVA nanofiber after solvent vapor treatment as a function of exposure time are shown in Fig. 4. For untreated PVA nanofiber mats, the tensile strength and Young’s modulus were approximately (5.3 ± 1.2) MPa and (36 ± 4) MPa, respectively. After vapor treatment, the mats showed a gradual increase both in tensile strength and Young’s modulus with an increase in evaporation time with all solvents used. For example, the tensile strength increased by over 60%, 90%, and 115% after treatment with DMR at a temperature of 40 °C for 2 h, 4 h, and 8 h, respectively. In addition, Young’s modulus was also increased by 36%, 66%, and 100% after treatment with DMF for 2 h, 4 h, and 8 h, respectively.

The mechanical properties of cross-linked nanofiber mats after treatment can be correlated with the SEM image shown in Fig. 3, where the gradual increase in modulus and tensile property of the mats is associated with solvent-induced fusion at nanofiber junction points [29, 32]; the condensation of vapor during post-treatment resulted in fusion between inter—fiber contacts in the mats. With an increase in exposure time, the amount of vapor that can induce nanofiber junctions is also increased, and when a greater number of nanofiber junctions are induced by the solvent vapor their mechanical properties increase. However, if too many
nanostructure junctions are induced by the solvent vapor, damage can occur to the nanostructure; it is therefore crucial to determine the optimum balance between the structure and the mechanical properties of PVA nanofiber after vapor treatment. It was also found that after evaporating PVA nanofiber for 8 h with DMSO, the nanofiber became slightly transparent due to the excessive amount of vapor, causing the nanofiber structure to become an ordinary film.

Based on mechanical properties and morphological structure, the PVA nanofiber mats with exposure times of 4 h, which showed a good improvement in mechanical properties and a stable structure, were chosen for further characterization. For convenience, the abbreviations PVA-NF-DMF treated, PVA-NF-methanol treated, and PVA-NF-DMSO treated are used to refer to nanofiber after solvent vapor treatment at a temperature of 40 °C for 4 h with DMF, methanol, and DMSO, respectively.

![Fig. 4](https://doi.org/10.1016/j.heliyon.2018.e00592)

**Fig. 4.** (a) Tensile strength and (b) Young’s modulus of PVA nanofiber mats before and after solvent vapor treatment with various solvents and treatment times.
3.2.2. Effect of solvent type

A comparison between the morphologies of PVA nanofiber mats after treatment with different solvents is shown in Fig. 5(a–d). Changes in morphology after treatment are clearly seen in the SEM image. PVA-NF-DMF treated mats show more intra-fiber bonding than other samples, which is the main reason for the superior improvement in mechanical properties, as shown in Fig. 5(e). These results are expected due

Fig. 5. SEM image of PVA nanofiber (a) before and after solvent vapor treatment with (b) DMF, (c) methanol, and (d) DMSO at a temperature of 40 °C for 8 h, and (e) Young’s modulus and tensile strength of PVA nanofiber mats with various solvent types at a temperature of 40 °C for 4 h.
to the high polymer-solvent affinity between PVA and DMF compared to the other treatments. Materials with similar Hansen Solubility Parameters have high affinities with each other [37]. The affinity between a polymer and a solvent is determined by their relative energy dispersion (RED), which is the ratio between solubility parameter distance ($R_a$) and the interaction radius ($R_0$) of the polymer. The solubility parameter distance can be calculated with the equation developed by Hansen and Skaarup (1967) [37] and is shown in Eq. (2),

$$\left( R_a \right)^2 = 4\left( \delta_D p - \delta_D s \right)^2 + \left( \delta_P p - \delta_P s \right)^2 + \left( \delta_H p - \delta_H s \right)^2,$$  

where $\delta_D$ is the density parameter of the dispersion interaction, $\delta_P$ is the density parameter of polar cohesive energy, and $\delta_H$ is the density parameter of the electron exchange parameter. Furthermore, the interaction radius ($R_0$) of PVA is reported in literature as being approximately 10.5 MPa$^{0.5}$ [37].

The RED of polymers and solvents used in this study are listed in Table 2, where RED = 0 means no energy difference, RED less than 1 indicates high affinity, and RED greater than 1 indicates a progressively lower affinity. PVA—DMF has a higher affinity compared to PVA—DMSO and PVA—Methanol; thus, the cross-linked effect is more significant. The polymer-solvent affinity value decreases from PVA—DMF to PVA—DMSO and PVA—Methanol in agreement with the increase in mechanical properties and changes in nanofiber morphology. Table 2 also lists the evaporation rate of the solvent at a temperature of 40 °C. Methanol has a higher evaporation rate than DMF and DMSO, which shows that more methanol molecules evaporate than DMF and DMSO during the same time and at the same temperature. However, the increase in mechanical strength and changes in morphology are less significant, because PVA-methanol has a lower affinity than DMSO and DMF.

Table 2. Relative Energy Density (RED), Hansen Solubility Parameters, and evaporation rates of solvents used in this study.

| Polymer/Solvent         | Hansen Solubility Parameters | RED $= \frac{R_a}{R_0}$ | Evaporating rate (mL/h)$^b$ |
|-------------------------|-----------------------------|--------------------------|-----------------------------|
|                         | $\delta_D$ | $\delta_P$ | $\delta_H$ | $\delta_{total}$ |                      |                  |
| Polyvinyl alcohol (PVA) | 14.7      | 14.1      | 14.9      | 25.2               | –                    | –                |
| N,N—Dimethyl formamide (DMF) | 17.4      | 13.7      | 11.3      | 24.9               | 0.43                 | 0.10             |
| Dimethyl Sulfoxide (DMSO)| 18.4      | 16.4      | 10.2      | 26.7               | 0.61                 | 0.01             |
| Methanol                | 15.1      | 12.3      | 22.3      | 29.6               | 0.72                 | 0.60             |

$^a$Based on experiment and computational calculation in Hansen et al. 2007 [37].

$^b$Based on volume solvent used in this study: 1.25 mL for 2 h, 2.50 mL for 4h, and 5.00 mL for 8h at a temperature of 40 °C.
The effect of the various solvent types on increasing the tensile strength and Young’s modulus are shown in Fig. 5(e). All the vapor solvents clearly improved the mechanical strength of PVA nanofiber but to different degrees. This result relates to the previous explanation about polymer–solvent affinity. The tensile strength of PVA nanofiber mats was increased by over 90%, 75%, and 50% after exposure at a temperature of 40 °C for 4 h with DMF, DMSO, and Methanol, respectively. In addition, the Young’s modulus of PVA nanofiber mats was also increased by over 67%, 45%, and 40% after exposure with DMF, DMSO, and Methanol, respectively. It is very evident that the sample treated with DMF vapor shows the highest improvement in both tensile strength and Young’s modulus. This result can be seen in the SEM image in Fig. 5(a–d) where morphological changes are more significant than those with other samples.

3.3. Thermal analysis

TGA/DTA analysis was used to determine the influence of solvents on the thermal stability of PVA nanofiber mats. Fig. 6(a) shows TGA/DTA curves of the mats before treatment at a heating rate of 10 °C/min. Four decompositional stages are clearly

![TGA/DTA curves](image)

**Fig. 6.** (a) TGA/DTA curves of PVA nanofiber untreated and (b) TGA of PVA nanofiber mats with and without various solvent vapor treatments at a heating rate of 10 °C/min.
evident on the DTA/TGA curve; the first occurs at a temperature of 62–127 °C with an endothermic peak at 102 °C that corresponds to moisture (removal of absorbed water molecules) in the sample; the second occurs at a temperature of 217–240 °C with an endothermic peak at 226 °C due to melting of the sample; and weight loss occurs in the third stage at a temperature of 240–360 °C with an exothermic peak at 360 °C, due to degradation of the polymer structure. In the final stage, the nanofiber mats decompose into carbon oxide and volatile hydrocarbons at a temperature above 360 °C with an exothermic peak at 427 °C. This result is in agreement with the experiment conducted by Es-Saheb et al. (2014) [24].

Fig. 6(b) shows the TGA curve of samples when different types of solvents were used in vapor treatment of PVA nanofiber mats. There were no significant changes between the decomposition stages and the decomposition temperatures before and after treatment. The endothermic peak corresponding with the moisture temperature of the sample increased from 99.6 °C to 102.7 °C, 106 °C, and 110.4 for untreated to DMF, methanol, and DMSO-treated nanofiber, respectively. In addition, the endothermic peak corresponded to the relative melting transition at a temperature of ~228 °C. Furthermore, degradation of the polymer structure decreased from 396.1 °C to 360.3 °C, 371.5 °C, and 376.5 °C for untreated to DMF, methanol, and DMSO treatment, respectively.

DSC is a valuable technique used to investigate the curing reaction of cross-linked polymers. Fig. 7 shows DSC thermograms over a temperature range of 50–300 °C for PVA nanofiber mats, both before and after solvent vapor treatments. As shown in Fig. 7, two obvious endothermic peaks can be seen in the curves. The first peak occurs at a temperature of 114 °C, 79 °C, 106 °C, and 85 °C for untreated, DMF,
Methanol, and DMSO treatments, respectively, and is related to moisture evaporation from the samples. The second endothermic peaks appears at around 229 °C for all samples and is the melting transition of PVA. This is in good agreement with the TGA result shown in Fig. 6. Table 3 shows the thermal properties of nanofiber PVA both before and after solvent vapor treatment.

The glass transition temperatures of the PVA nanofiber before and after vapor treatment are shown in Table 3. The value was decreased from 88.5 °C for the untreated sample to 63.5 °C, 78.0 °C, and 55.0 °C, for DMF, methanol, and DMSO treatments, respectively. Other studies have stated that the decrease in the glass transition temperature is due to plasticizing of the solvent [38, 39]: solvents plasticize the nanofibers, making them more flexible and enhancing fusion at fiber junction points and solvent vapor treatment increases the rigidity of the membrane even though fibers plasticize [29].

Table 3 shows that DSC crystallinity of the samples decreased after treatment, which indicates that the sample became more amorphous. DSC crystallinity of nanofiber mats was calculated using Eq. (1), based on the DSC curve shown in Fig. 7. In recent studies, DSC crystallinity calculation has largely been used to validate X-ray diffraction (XRD) results [40, 41]. The authors’ previous study [25] showed that PVA nanofiber has a low degree of crystallinity, and this agrees with XRD results. Low crystalline polymers (amorphous) usually have transparent properties, and the crosslinking of PVA nanofiber mats with the vapor treatment make the nanofibers more transparent due to excessive melting and the plasticizing role of the solvents. However, higher crystalline polymers usually have higher mechanical properties due to their ordered structure [42, 43]. A polymer with highly ordered crystallites has fewer boundary crystals (defects), which cause a decrease in mechanical properties. However, in this study, the higher crystalline (DSC crystallinity) sample has a lower mechanical strength with respect to the increase in nanofiber density from solvent vapor treatment. The mechanical properties of the membrane depend on its density and its ordered structure. When solvent vapor treatment was conducted, the density of the

| Sample Treatment          | At glass phase transition ($T_g$) | At melting phase transition ($T_m$) | DSC Crystallinity (%) |
|---------------------------|-----------------------------------|-----------------------------------|-----------------------|
|                           | $T_g$ (°C) $\Delta H$ (J/g)       | $T_m$ (°C) $\Delta H$ (J/g)       |                       |
| PVA-NF-Untreated          | 88.5 176.45                       | 229.75 57.50                      | 41.49                 |
| PVA-NF-DMF treated        | 63.5 82.46                        | 229.55 46.10                      | 33.27                 |
| PVA-NF-Methanol treated   | 78.0 115.21                       | 229.03 45.63                      | 32.93                 |
| PVA-NF-DMSO treated       | 55.0 84.17                        | 229.18 37.33                      | 26.94                 |
nanofiber increased, thereby causing an increase in the tensile strength and Young’s modulus. Therefore, the change in crystallinity has a less significant effect compared to modification of the nanofiber density; therefore, the tensile strength and Young’s modulus of PVA nanofiber mats are increased.

4. Conclusions

The effect of solvent vapor treatment on nanofiber PVA was clearly observed using scanning electron microscope (SEM). Vapor solvent affects nanofiber morphology by producing solvent-induced fusion at nanofiber junction points, which forms physical cross-links in nanofiber mats, thereby increasing the mechanical properties of the nanofiber. Both the tensile strength and Young’s modulus of PVA nanofiber mats increased after solvent vapor treatment with all the solvents used in this study. The effect of DMF vapor was the most significant in increasing the mechanical properties of PVA nanofiber, due to the higher polymer-solvent affinity compared to the other solvents. Results show that solvent vapor treatment can be employed as a promising alternative treatment to increase the mechanical properties of electrospun nanofibers.

Declarations

Author contribution statement

Aditya Rianjanu: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Ahmad Kusumaatmadja: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Eko Agus Suyono: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Kuwat Triyana: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by the funding from Ministry of Research Technology and Higher Education, the Republic of Indonesia under Contract Number 4580/UN1-P.III/LT/DIT-LIT/2016.

Competing interest statement

The authors declare no conflict of interest.
Additional information

No additional information is available for this paper.

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