Chapter 3

Fabrication of Highly Aligned Poly(Vinyl Alcohol) Nanofibers and its Yarn by Electrospinning

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Additional information is available at the end of the chapter

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Abstract

In the conventional electrospinning method, fibers are randomly deposited and form nonwoven structures; however, highly aligned micro- or nanofiber and its yarn may only be applicable for the fields, including composites, clothing, textiles, and microelectronics. The elementary principle to obtain uniaxially arranged nanofiber array is to regulate the electric field distribution by using assistant electrode or modified collecting device. The potential applications of conventional electrospun poly(vinyl alcohol) (PVA) fiber in the preparation of ultrafine separation filters, biodegradable mats, etc., have been described by many researchers. Highly aligned PVA nanofibers were prepared using a modified electrospinning process at the optimum conditions, and a twister added modified electrospinning apparatus was used to prepare twisted nanofiber yarn. The diameter and arrangement of the electrospun PVA nanofibers were characterized using FE-SEM. To study the effect of applied voltage and rotational velocity on the alignment rate of the nanofibers, different voltages and rotational velocity were applied during modified electrospinning, keeping other parameters unchanged. To measure the melting temperature and crystallinity of aligned nanofibers, differential scanning calorimetry and X-ray diffraction measurement were performed, respectively. The fabricated highly aligned nanofiber and its yarn might have a practical use of devices for microelectronics.

Keywords: poly(vinyl alcohol), aligned nanofiber, yarn, electrospinning, centrifugal jet spinning

1. Introduction

Generally, electrospun nanofibers often exhibit random orientation due to the bending and whipping movement of the electrospinning jet [1]. Control over the unidirectional nanofibers is required for specific applications including composite materials, electrochemical sensing, reinforcements, bone, blood vessel engineering, and tissue engineering [2]. Beside, production of yarn has been of great interest as it is necessary for weaving and knitting. It is more convenient to handle yarn instead of single nanofibers as they are strong enough without the demand of precise and sophisticated equipment [3]. As a result, current interests have been shifted toward the electrospinning of aligned nanofibers and its yarn and some reports are available on them.

A facile route was established by Rakesh et al. to control the alignment of electrospun multi-walled carbon nanotube/reinforced poly(vinyl alcohol) (PVA) nanofibers using slotted collector geometries [4]. They showed that the introduction of an insulating into a conductive collector considerably influences the electrostatic forces acting on a charged fiber. Also, they reported in the same study that among different collector geometries, rectangular and slotted collectors with circular ends present good fiber alignment over a large collecting area. Bicomponent-aligned nanofibers of N-carboxyethyl chitosan and PVA were fabricated by Mincheva et al. [5]. Also, they reported in the same paper that 1D-, 1D-transversery, or 3D fiber alignment was fabricated depending on the type of the collector used.

To use the full potential of electrospun nanofibers, it is necessary to assemble into well-ordered structures. Aligned structures nanofibers have also been proven to be better quality for tissue engineering applications, stimulating controlled cell growth, adhesion, and proliferation featuring those of the natural extracellular matrix [6, 7].

Lately, a number of techniques have been developed to fabricate aligned electrospun nanofibrous structures, for example, the use of a rotating mandrel collector, dual-grounded collection plate, a copper wire drum, a scanning tip, a water reservoir collector, dynamic liquid support system, two oppositely metallic spinneret, multiple field, and parallel auxiliary electrodes [8]. The different fiber alignment technique has been used by various research scientists. Zussman et al. reported on a system for producing the ordered fabrication of nanofibers into the crossbar nanostructures. In this technique, the collector disk fitted with a table that can collect the nanofibers and can be revolved about the *z*-axis, each fiber aligned at a set angle to the layer to create layers of nanofiber arrays below, the collector's disk is temporarily stopped and the table revolved the required number of degrees (**Figure 1(A)**) [9]. Katta et al. presented a simple and successful technique for spinning sheets with one centimeter wide strips of aligned nanofibers. Copper wires placed regularly in the form of a round drum as a collector of the electrospun nanofibers was used in this technique and aligned nanofiber layers can be assembled easily without distressing the aligned structure (**Figure 1(B)**) [2]. The conventional method for electrospinning has been modified by Li et al. to fabricate uniaxially aligned nanofibers arrays over larger areas. The reason for the success of this technique was the use of a collector consists of two conductive strips isolated by an insulating gap of flexible width (**Figure 2(A)**) [1]. **Figure 2(B)** and **(C)** show two pairs of conductive bars parted by an insulating material [5]. A facile and reproducible method was reported by Liu et al. in which they

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established a novel annular collector to arrange the fibrous bundle and identical yarn with well-aligned submicron fibers done by electrospinning, predrafting, and successive twisting (**Figure 3(A)** and **(B)**) [10]. Tamura et al. studied about the fabrication of novel uniaxially aligned ultrafine sulfonated copolyimide nanofibers using an electrospinning apparatus consists of a removable collector made of two conductive aluminum foils and a glass plate insulator (**Figure 4**) [11].

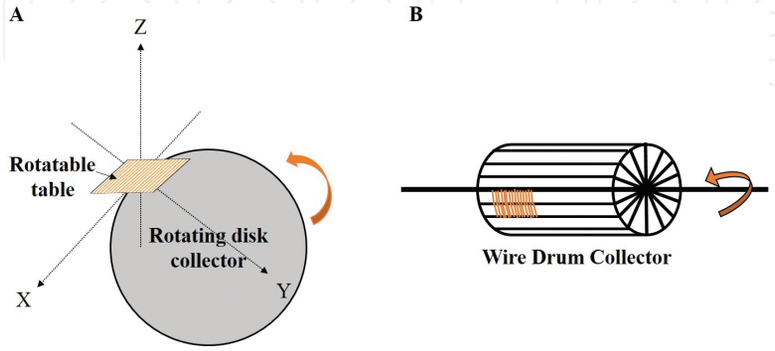

Figure 1. Schematic illustration of the electrospinning method to prepare aligned nanofiber. (A) Showing the collector disk equipped with a table that can collect the nanofiber and can be rotated about the *z*-axis [9] and (B) presenting Plexiglas disk with copper wires that can collect nanofibers as stratified layering [2].

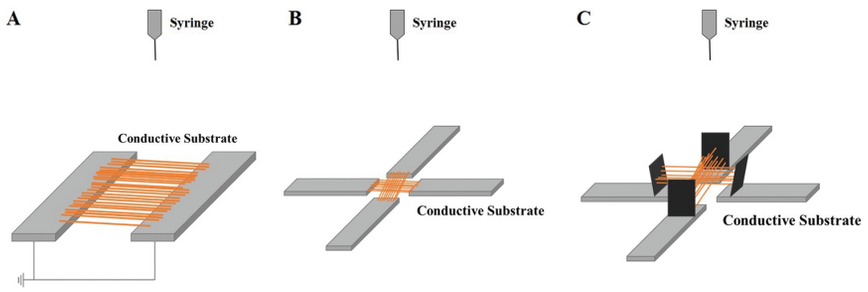

Figure 2. Schematic representation of the collectors used for preparing aligned nanofiber (2A = Ref. [1], 2B and 2C = Ref. [5]).

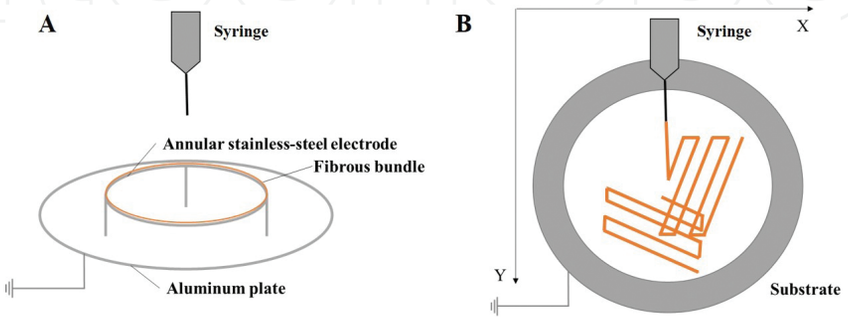

Figure 3. Schematic representation of the electrospinning process for preparing the annular submicron fiber bundle (3A = Ref. [10], 3B = Ref. [27]).

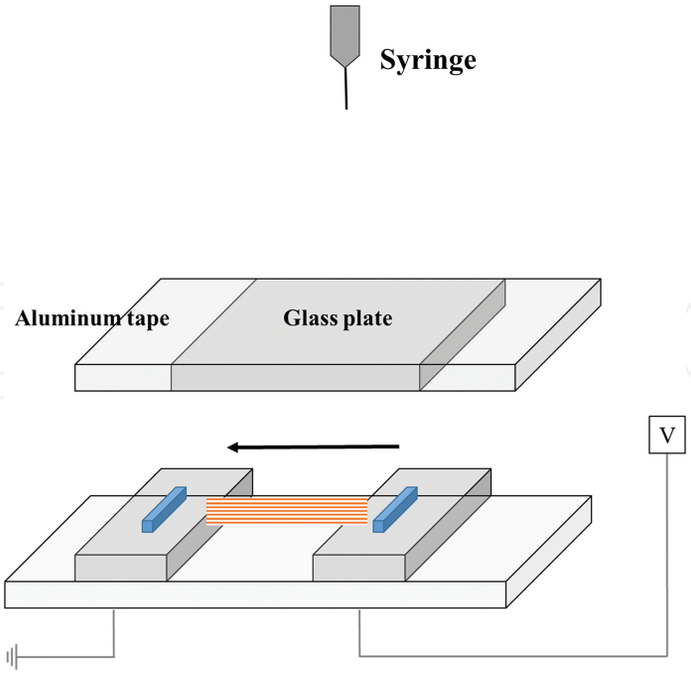

Figure 4. Schematic diagram of the electrospinning method and the collector was composed of two conductive aluminum foils and a glass plate insulator and the collector could be removed from the apparatus [11].

In the beginning, most of the work on electrospinning of nanofiber yarns was actually concentrated on nontwisted nanofiber bundles. Despite twist can be intruded by a postelectrospinning treatment, it is now highly favored that twists can be given directly to continuous nanofiber yarns from an electrospinning process.

In this investigation, we demonstrated a novel parallel collector to obtain the highly aligned PVA nanofibers through modified electrospinning, and a twister added modified electrospinning apparatus was used to prepare twisted nanofiber yarn. The effect of applied voltage and rotational velocity of twister on the alignment rate of the nanofibers were evaluated.

2. Experimental

2.1. Materials

PVA (number-average degree of polymerization of 1700, M_w = 89,000–98,000, fully hydrolyzed, degree of saponification = 99%) was purchased from the DC Chemical Co., Seoul, South Korea. For preparing all solution doubly distilled water was used.

2.2. Preparation of spinning solution

PVA solutions were prepared by dissolving PVA in doubly distilled water under magnetic stirring for 2 h at 80°C followed by cooling to room temperature and various PVA concentrations were used (5 and 7.5 wt.%). For centrifugal jet electrospinning only 5 wt.% PVA was used.

2.3. Electrospinning

For general electrospinning method, PVA solutions were carefully transferred into a syringe and a syringe pump was used to deliver the solution through the blunt needle with a regulated solution feeding rate. Electrospinning was performed under various electric fields (CHUNGPA EMT Co., South Korea), which was applied to the solution using an alligator clip attached to the syringe needle. To collect fibers an electrically grounded aluminum foil was placed at a certain vertical distance from the needle tip. For modified electrospinning method, we used parallel plane collectors to get uniaxially aligned fibers, which consist of two strips or plates of metallic collectors connected to the negative voltage and the needle was connected to the positive voltage. In this method, the electrospinning jet is drawn in between the two plates, ensuring the deposition of uniaxially aligned fibers perpendicular to the plates.

During the electrospinning process, PVA solutions were carefully transferred into a syringe and a syringe pump was used to deliver the solution through the blunt needle with a regulated solution feeding rate. Electrospinning was performed under various electric fields (CHUNGPA EMT Co., South Korea), which was applied to the solution using an alligator clip attached to the syringe needle. To collect fibers an electrically grounded aluminum foil was placed at a certain vertical distance from the needle tip. For getting twisted fibers a rotating twister was attached before the grounded rotating drum collector as shown in **Figure 5**. At first the solidified fibers were twisted by the twister, subsequently accumulated around the rotating drum collector.

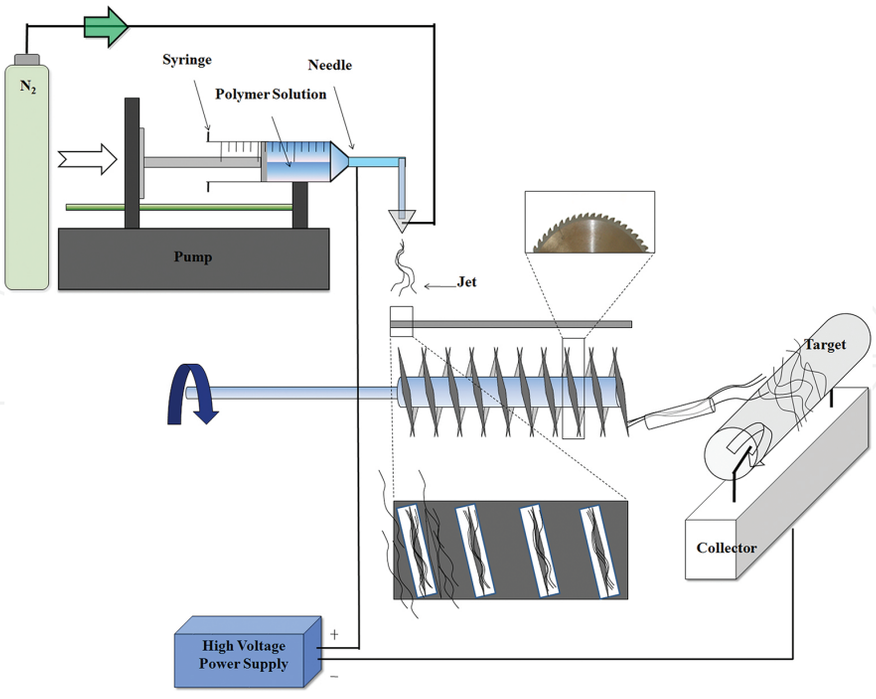

Figure 5. Schematic illustration of a twister added modified electrospinning apparatus to prepare twisted aligned nanofibers yarn.

2.4. Centrifugal jet electrospinning

Generally, the centrifugal jet spinning is composed of motor, disk containing spinneret and collector (**Figure 6**). In this method, aligned nanofibers are fabricated by exploiting high-rotational force, rotating polymer solution jets to eject fiber.

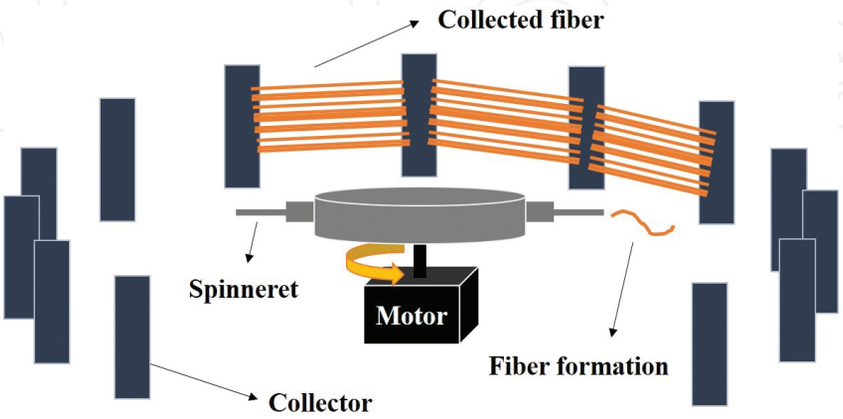

Figure 6. Schematic illustration of the general centrifugal jet spinning apparatus.

In this study, we have made a setup of centrifugal electrospinning on the basis of conventional electrospinning and centrifugal spinning. As shown in **Figure 7**, the syringe is attached to a smaller diameter pipe and fixed vertically above a circular rotating disk containing many metallic needles like ejection path for polymer solution. The disk is attached to a speed-adjustable motor and TCD is 15 cm. A round case-like collector made of metallic wire placed around the rotating disk for collecting the nanofibers. The high voltage was applied between the ejection needle and collector. The polymeric jet originated from the ejection end under the action of electrical force and centrifugal force and the jets are extended by the repulsive force of charges on the jets [12]. Highly aligned ultrafine PVA nanofibers are fabricated after the jets solidify and fall onto the collector.

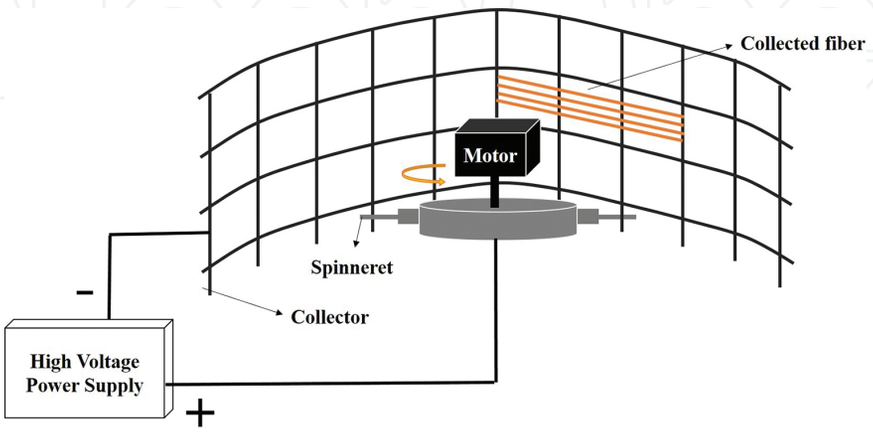

Figure 7. Schematic illustration of the centrifugal jet electrospinning apparatus.

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2.5. Characterization

The morphology of PVA nanofibers and its yarn were examined using a FE-SEM (SU8220, Hitachi, Japan). From the FE-SEM images the fiber diameter was measured. Photoshop 7 was used to measure the average fiber diameter and at least 20 different fibers and 100 different segments were randomly selected from each image. The degree of nanofibers alignment was studied against different voltages keeping other parameters constant. To measure the melting temperature and crystallinity of aligned nanofibers differential scanning calorimetry and X-ray diffraction measurement were performed, respectively. To determine the degree of nanofiber alignment, several FE-SEM images were captured from each sample.

3. Results and discussion

3.1. Fabrication of highly aligned PVA nanofibers by electrospinning

PVA is a well-known hydrophilic, semicrystalline polymer and has received great attention due to its good chemical resistance, good thermal stability, good physical properties, excellent biocompatibility, and low price [13, 14]. The potential applications of electrospun PVA fiber in the preparation of ultrafine separation filters, biodegradable mats, etc. have been described by many researchers [14, 15]. As a simple and versatile process electrospinning is offering unique capabilities for preparing fibers from polymer solutions with diameters ranging from the nano- to microscale which generated interesting applications in fields of protective clothing, filtration, drug delivery, self-cleaning, tissue engineering, electronic and photonic devices, etc. [16, 17]. However, the function is somewhat limited so far, as the maximum electrospun fibers are in the form of isotropic nonwoven mats [18]. As a result current interests have been shifted toward electrospinning-aligned nanofiber yarn for the purpose of use in microelectronics, photonics, and in a variety of electrical, optical, mechanical, and biomedical applications [8]. Due to the high surface area, porous structure, and functional molecules and nanomaterials adopting ability (e.g., nanoparticles and nanotubes), nanofibers have been used in various areas including batteries, biomedical, sensors, fuel cells, nanocomposites, and protective clothing [19–25]. Due to the "whipping instability" of the electrospinning jet, typical electrospun nanofibers are usually collected as nonwoven or randomly oriented structures, since disordered orientation and low mechanical strength of the fibrous structure have restricted their applications, early studies were focused on regulating the fiber alignment.

Aligned fibers are considered as potential candidates for the design of directional optical components, for instance waveguides and lasers [26]. To obtain aligned electrospun fibers, several approaches have been established, however, parallel electrode method has gained more attention due to the higher degree of alignment of the fibers [26, 27]. In parallel electrode method, aligned nanofibers are obtained through the manipulation of the electric field that was manipulated by using two parallel plates (gap collector) joined with grounded electrode [1, 28]. It is possible to get a high degree of fiber alignment using this method, and the produced fibers can be easily applicable for device fabrication.

In this section, we are reporting about the preparation of highly aligned PVA nanofibers using a modified electrospinning apparatus composed of two parallel vertical plate collectors. The diameter and arrangement of the electrospun PVA nanofibers were characterized using a field emission scanning electron microscope (FE-SEM). The degree of nanofiber alignment was studied against different voltages keeping other parameters constant. The melting temperature and crystallinity of aligned nanofibers with different voltages were also studied.

3.1.1. Morphological differences of nanofibers

Figure 8(A) and **(b)** show the FE-SEM images of electrospun nanofibers prepared by the general electrospinning method and modified electrospinning method, respectively. It is found that although smooth, defect-free and round-shaped fibers are collected using both the modified and unmodified electrospinning method, the alignment of the nanofibers is very different for these two methods. Manipulation of the electric fields that were manipulated by using two parallel vertical plates connected with positive voltage coupled with the repelling force from the residual charges on the electrospun nanofibers ensure good alignment of the electrospun nanofiber as shown in **Figure 8(B)**. In contrast, a regular oriented distribution of electrospun fibers cannot be achieved using unmodified collector as shown in **Figure 8(A)**.

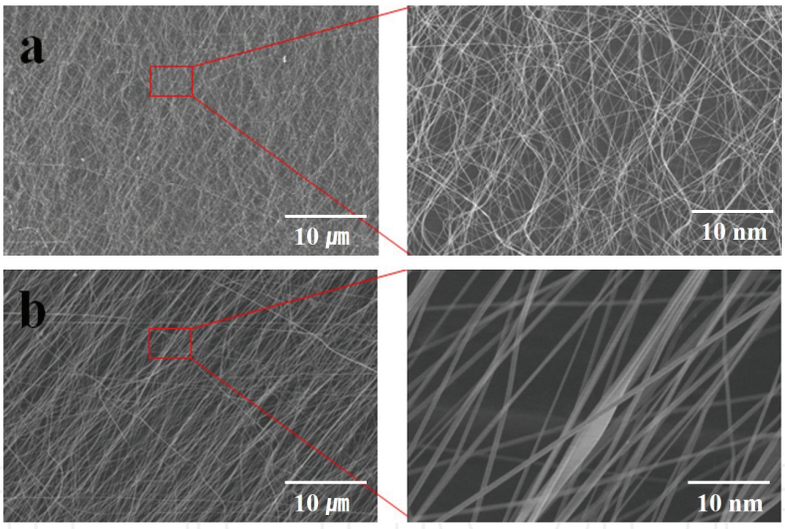

Figure 8. FE-SEM images of PVA nanofiber prepared by (a) general electrospinning method and (b) modified electrospinning method. (Concentration of PVA solution = 7.5 wt.%, TCD = 15 cm, and applied voltage = 10 kV.)

The FE-SEM-measured nanofiber diameter distributions for both preparation methods are shown in **Figure 9** for the purpose of comparison. In the case of the nonaligned PVA nanofibers prepared using general electrospinning methods (**Figure 9(A)**), the average diameter value is $\langle D \rangle$ = 243.7 nm with a standard deviation of σ = 82.82 for N = 100 measurement. In case of aligned nanofiber prepared by modified electrospinning method (**Figure 9(B)**) value of $\langle D \rangle$ = 1013.9 nm and σ = 613.2 were estimated for N = 100 measurement. These statistics illustrated that a better control over nanofiber diameter was gained with the nonaligned PVA nanofibers compared to aligned nanofiber.

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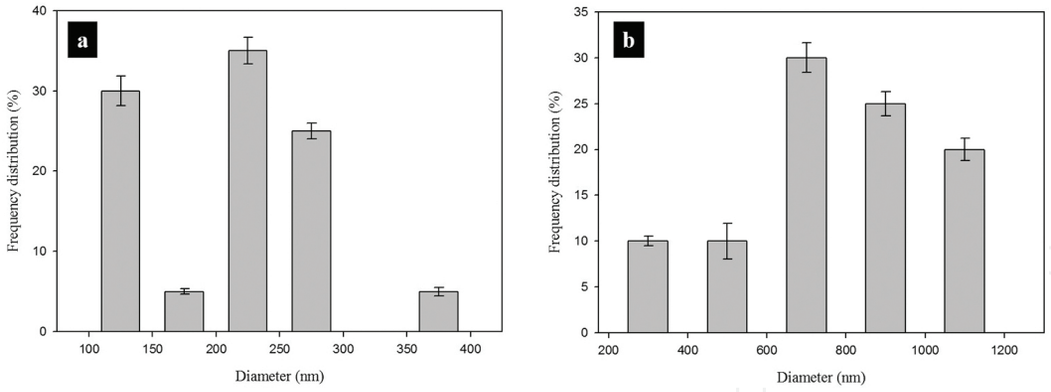

Figure 9. Diameter distribution of PVA nanofiber prepared by (a) general electrospinning method and (b) modified electrospinning method. (Concentration of PVA solution = 7.5 wt.%, TCD = 15 cm, and applied voltage = 10 kV.)

3.1.2. Effect of applied voltage on melting temperature and crystallinity of nanofiber

The melting temperature and percentage of crystallinity of aligned PVA nanofiber prepared by modified electrospinning method at various voltages are presented in **Figure 10**. As can be seen, applied voltage plays a pivotal role on both melting temperature and crystallinity rate of aligned PVA nanofiber. The results showed that both melting temperature and crystallinity rate increase as the applied voltage increased. For example, consider the value of melting temperature and crystallinity rate at voltage 10, 12, 14, 16, 18, and 20 kV. The numerical values for the melting temperature are 223, 223.8, 224.6, 225.2, 226, and 227°C and corresponding values for crystallinity rate are 50, 50.4, 51.5, 52.1, 52.8, and 53.2%, respectively. From the results it is clear that the higher melting temperature and crystallinity rate of aligned PVA nanofiber can be obtained at applied voltage 20 kV.

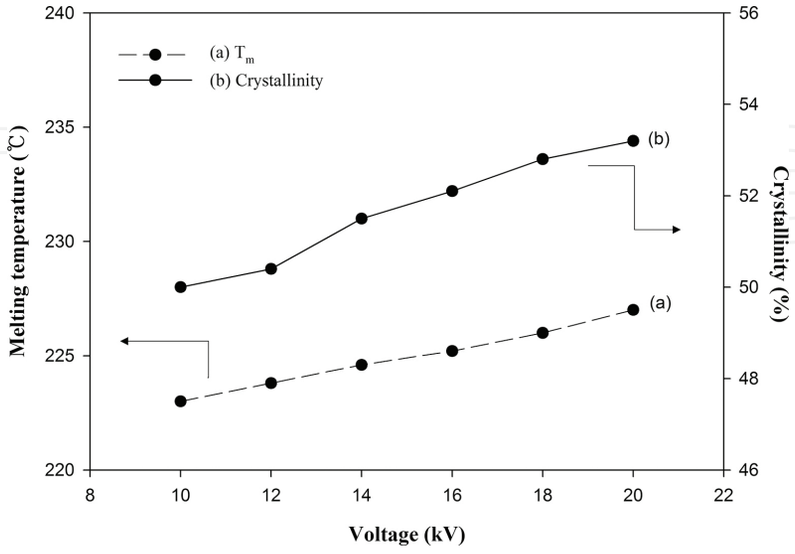

Figure 10. Effect of voltage on melting temperature and degree of crystallinity of aligned PVA nanofiber. (PVA solution concentration = 5 wt.%, TCD = 10 cm).

3.2. Preparation-aligned PVA nanofiber yarn using a twister added modified electrospinning method

One-dimensional nanomaterials having diameters less than 1 μm (1000 nm), and an aspect ratio (length/diameter) larger than 100:1, are defined as nanofibers or superfine or ultrathin fibers. Nanofibers are also called as submicron fibers when they are in the range of 100–1000 nm [29–31]. As we know, a conventional electrospinning process requires the application of electrostatic force between polymer solution kept in a syringe and a counter metal electrode, for example, as a plate or a rotating drum placed at a suitable distance. The electrostatic forces overcome the surface tension of the polymer solution if sufficient high electrical field is applied, as a result a thin jet can be ejected from the drop of polymer solution formed at the tip of the spinneret. At first the charged jet undergoes a stable stretching, however, soon it starts bending and whipping randomly due to further stretching of the jet and evaporation of solvent [32, 33]. It is possible to collect electrospun fibers as oriented parallel to the direction of rotation [34]. Yarns can be interlaced into many fibrous structures by various processes; however, single nanofibers being fragile and thin are not appropriate for such processes, and sophisticated equipment is required for exact handling of these fibers [35].

Various attempts had been taken by the researchers to obtain nanofibers yarn. Formhals attempted a method to produce nanofiber yarns from electrospun nanofibers and reported in 1934. He described the experimental setups of producing polymer filaments using electrostatic forces in a series of patents. In the beginning, most of the works on electrospinning of nanofiber yarns were actually concentrated on nontwisted nanofiber bundles. Despite twist can be intruded by a postelectrospinning treatment, it is now highly favored that twists can be given directly to continuous nanofiber yarns from an electrospinning process. The deposition of nanofibers in the form of a narrow strip using a series of charged rings in the electrospinning zone was demonstrated by Deitzel et al. in 2001, both the charged rings and the surface charge on the jet had the same polarity that can enhance the downward force on the jet resulted in nanofiber deposition in a narrow strip (0.6 cm wide) on the target of rotating drum [36]. Theron et al. [37] demonstrated an electrostatic field-assisted assembly technique in combination with the dynamic rotating collector to create individual nanofibers positioned and aligned. In this method, a tapered wheel-like disk made of aluminum was used to collect bundles of nanofibers. The jet emerged from the droplet, at first form an envelope cone after that shrink to form an inverted cone, once it reached the sharp-tapered edge of the wheel collector which had a strong converging electric field. Accordingly, nanofibers would preferentially deposit on the wheel edges, which were accumulated in a parallel array due to the rotation of the wheel. Teo and Ramakrishna [38] described the fabrication of nanofiber bundles by collecting them across two negatively charged steel blades followed by dipping them in water that was thus required to assemble the fibers together by the force of water surface tension. The resulting fiber bundles can be transferred into other substrates, and to be twisted or braided manually.

In this section, we are reporting about a novel twister added self-bundling electrospinning method for generating continuous twisted aligned PVA electrospun fiber yarn. Compared with conventional electrospinning setup, the special thing in this process is that a twister is used to induce the self-bundling of polymer nanofibers before deposited on the collector. The diameter

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and arrangement of the electrospun PVA nanofibers were characterized using FE-SEM. The degree of nanofibers alignment was studied against different voltages and rotational velocity of twister keeping other parameters constant.

3.2.1. PVA-aligned nanofiber yarn morphology

Figure 11 represents the FE-SEM image of the twisted yarn of PVA prepared using rotational velocity 25 rpm, applied voltage 15 kV, TCD 15 cm, and PVA solution concentration at 5 wt.%. For the following study, we have prepared the twisted yarn at low rotational velocity. As can be seen most of the filaments included ae twisted. As showing in **Figure 11**, the fiber surface reveals that highly twisted, smooth, uniform with a higher alignment rate were obtained.

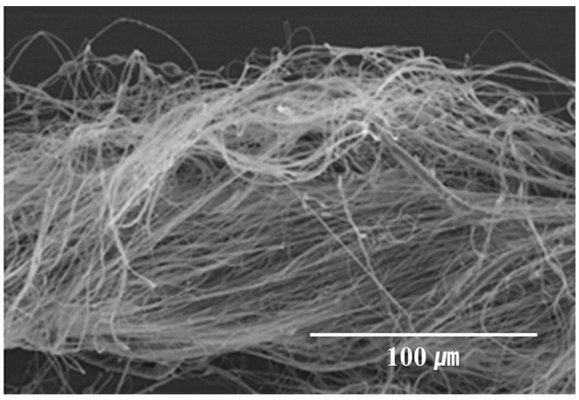

Figure 11. FE-SEM image of twisted aligned PVA nanofiber yarn prepared by twister added modified electrospinning apparatus. (PVA solution concentration= 5 wt.%, TCD = 15 cm, applied voltage = 15 kV, rotational velocity = 25 rpm).

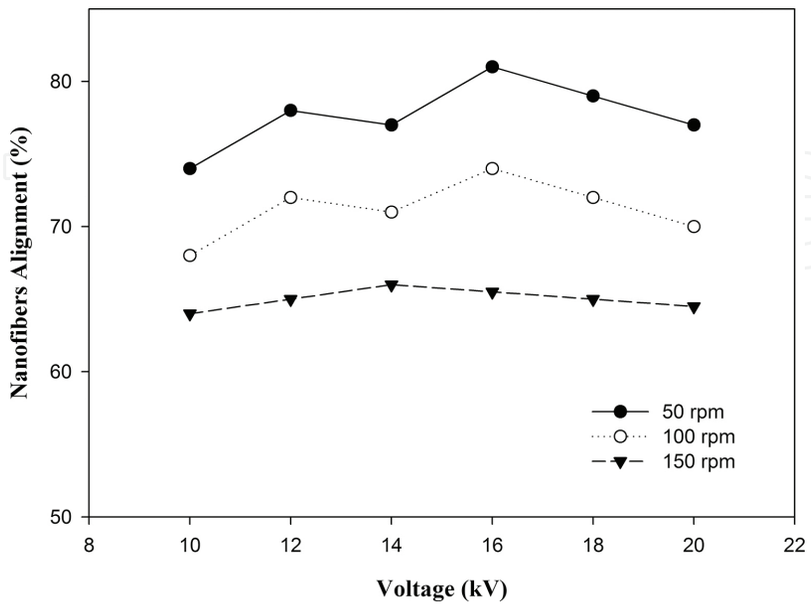

Figure 12. Effect of voltage and rotational velocity on the degree of alignment of twisted PVA nanofiber.

3.2.2. Effects of voltages and rotational velocity on degree of nanofiber alignment in yarn

During electrospinning process, voltage and rotational velocity of twister play significant role in nanofiber alignment rate. A series of experiments were carried out by changing the applied voltage and rotational velocity in the range of 10–20 kV and 50–150 rpm, respectively (**Figure 12**). As illustrated, voltage has no significant effect on fiber alignment rate, however, considerable change was found on nanofiber alignment at various rotational velocities. We measured nanofiber alignment rate against three different rotational velocities of twister including 50, 100, and 150 rpm at various voltages in the range of 8–20 kV. A higher degree of nanofiber alignment was found at the rotational velocity of 150 rpm. In contrast, the lowest degree of nanofiber alignment was obtained at 50 rpm. It can be also seen that the maximum degree of nanofiber alignment was obtained at 150 rpm and 16 kV.

3.2.3. Effects of rotational velocity on nanofiber morphology in yarn

Figure 13 shows several FE-SEM images of various samples taken from the twister-added rotating drum collector. Several sets of experiments were conducted at various rotational velocities of twister, and images were captured to confirm twisting and alignment. To acquire different perspective, images were taken at various magnifications. As seen in the FE-SEM images, well-aligned, highly twisted and thin nanofibers are present at 150 rpm. And the possible reason of smaller diameter nanofiber is the removal of residual solvent from the nanofibers due to higher rotational velocity. Beside, beads are seen at 100 and 150 rpm. Finally, it can be concluded that uniform, highly twisted, and well-aligned nanofiber with less beads defects are only achievable at 150 rpm.

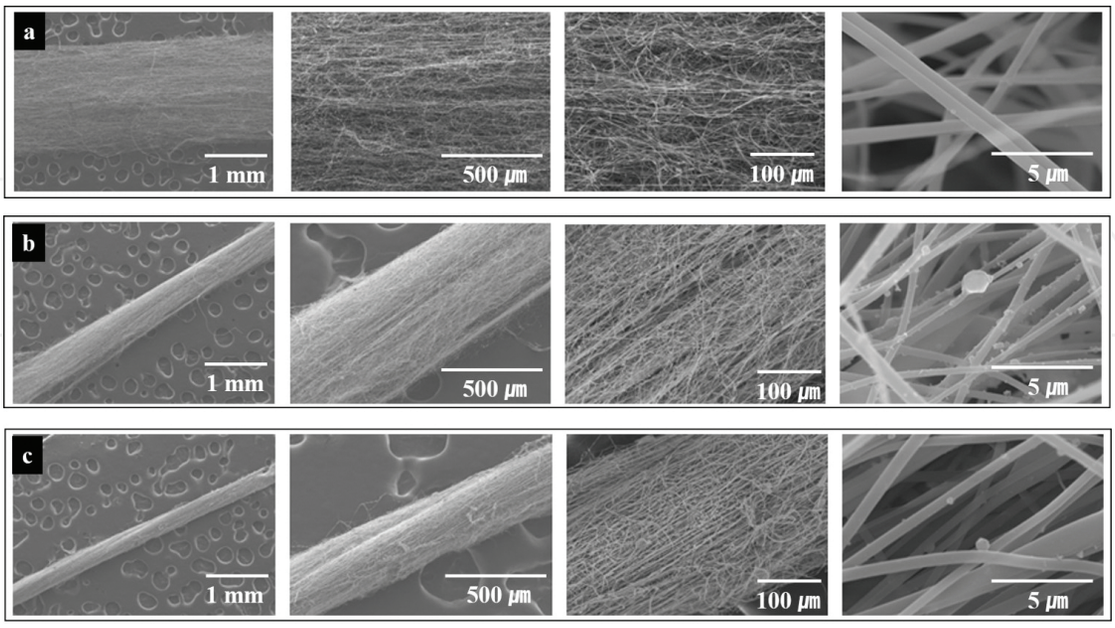

Figure 13. FE-SEM images of aligned twisted PVA nanofiber yarn prepared at different rotation velocity (a) 50 rpm, (b) 100 rpm, and (c) 150 rpm. (PVA solution concentration = 7.5 wt.%, TCD = 15 cm, and applied voltage = 16 kV).

3.2.4. Effects of rotational velocity on diameter distribution of nanofiber in yarn

The diameter distributions of aligned PVA nanofiber yarn gained at three different rotational velocities of twister were given in **Figure 14**. We considered three rotational velocities of twister including 50, 100, and 150 rpm. Smaller average fiber diameter and a large amount of thin fibers with diameter bellow 400 nm were found at 150 rpm (**Figure 14(C)**). On the other hand, a narrower distribution of fiber diameters was observed at 100 rpm (**Figure 14(B)**), however, beaded nanofiber with lower alignment rate was observed at this rotational velocity (**Figure 13**). Comparatively less control in the fiber diameter with average diameter 444 nm was seen at 50 rpm.

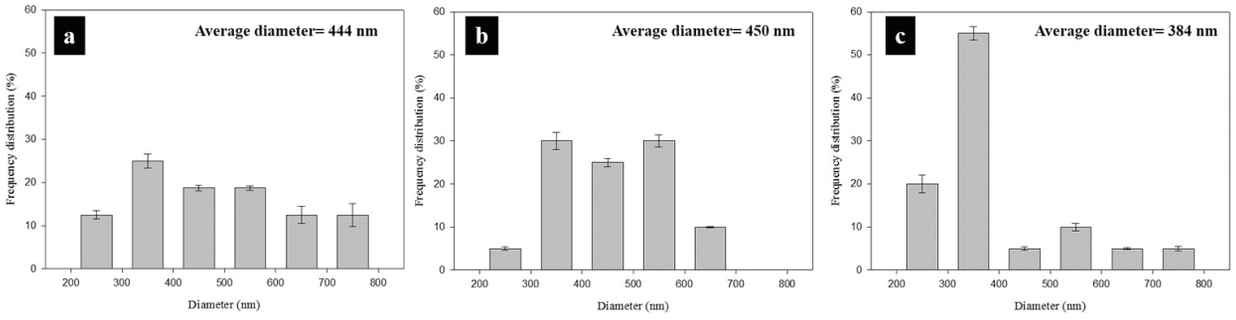

Figure 14. Diameter distribution of aligned twisted PVA nanofiber yarn prepared at different rotation velocity (a) 50 rpm, (b) 100 rpm, and (c) 150 rpm. (PVA solution concentration = 7.5 wt.%, TCD = 15 cm, and applied voltage = 16 kV).

3.2.5. Effects of rotational velocity on nanofiber morphology in yarn

The FE-SEM images of the PVA yarn collected at 200 rpm are presented in **Figure 15**. Rotation velocity of twister has considerable effect on nanofiber diameter [39]. From the magnified FE-SEM image (**Figure 15(C)**), it is clear that smaller diameter and well-aligned nanofibers were fabricated. In addition, it is also seen that smooth, defects free, and round shape nanofibers exist.

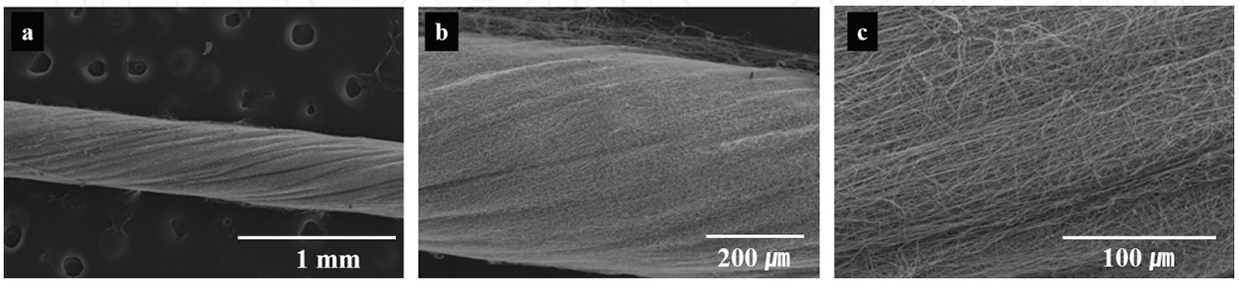

Figure 15. FE-SEM images of (a) aligned twisted PVA nanofiber yarn prepared at rotational velocity of 200 rpm. The images (b) and (c) are magnified form of image (a). (PVA solution concentration = 7.5 wt.%, TCD = 15 cm, and applied voltage = 16 kV).

3.3. Fabrication of highly aligned PVA nanofibers by centrifugal jet electrospinning

Recently, centrifugal jet spinning technique has drawn much attention of the scientists for the production of nanosized fiber due to its amazing characteristics, for example, large-scale production rate, facile, highly efficient, low cost fabrication technique, etc. [40]. The method uses centrifugal forces together with the viscoelastic properties and the mass transfer characteristics of spinning solutions to support the controlled thinning of a polymer solution filament into nanofibers [41].

Many researchers have tried centrifugal jet spinning method to prepare aligned nanofiber for various purposes. Badrossamay et al. [42] studied a facile technique for fabricating aligned three-dimensional nanofiber structures by exploiting high-speed, rotating polymer solution jets to eject fiber. They also demonstrated the usefulness of this technique for building uniaxially aligned nanofiber structures necessary for tissue engineering. A novel and effective centrifugal electrospinning setup with rotating polymer solution jets was demonstrated by Liu et al. to prepare uniaxially aligned and cross-aligned arrays of ultrafine polymer fibers [43]. Amalorpava Mary et al. had attempted a novel method to obtain centrifugal spun fibrous web as a drug [44]. On considering the huge prospective and effectiveness of this technique, we have also made some attempts to make centrifugal spun nanofibers.

The centrifugal jet spinning system was composed of a DC hobby motor (9–18 V, Radio Shack) powered hollow chamber with two orifices passing through the chamber wall and a set of product collecting posts. Teflon tubes (outer diameter of 15 mm and an inner diameter of 10 mm) were used to make spinning chamber. The diameter of the orifices present in the wall of the spinning chamber was 500 μm. It is possible to adjust the distance between the center of the chamber and the product collecting posts. At a particular flow rate, spinning solutions were continuously fed into the chamber and the centrifugal force exceeded the capillary force of the spinning solution in the orifice as the spinning chamber spins. Consequently, spinning solution jet is ejected from the rotating chamber and by adjusting the voltage applied on the motor the rotational speed of the chamber can be changed [41].

In this section, we are reporting about the fabrication of highly aligned PVA nanofibers by a unique and efficient centrifugal electrospinning setup with rotating polymer solution jets. The developed fibers were morphologically characterized by FE-SEM and the results showed that highly aligned PVA nanofibers were successfully assembled.

3.3.1. Morphology of centrifugal jet electrospun-aligned nanofibers

Figure 16 shows the FE-SEM pictures of highly aligned PVA nanofibers (PVA solution concentration was 5 wt.%), which were obtained at the optimized conditions (TCD = 15 cm, applied voltage = 15 kV, and rotational velocity = 5000 rpm). To get clear idea images were taken at various magnifications. As seen in the FE-SEM images excellent alignment is present. From **Figure 16(D)**, it is clear that well-aligned nanofibers with higher alignment rate can be produced through our new centrifugal jet electrospinning setup. Excellent properties of nanofibers are observed, including uniform, feed free, and smooth surface.

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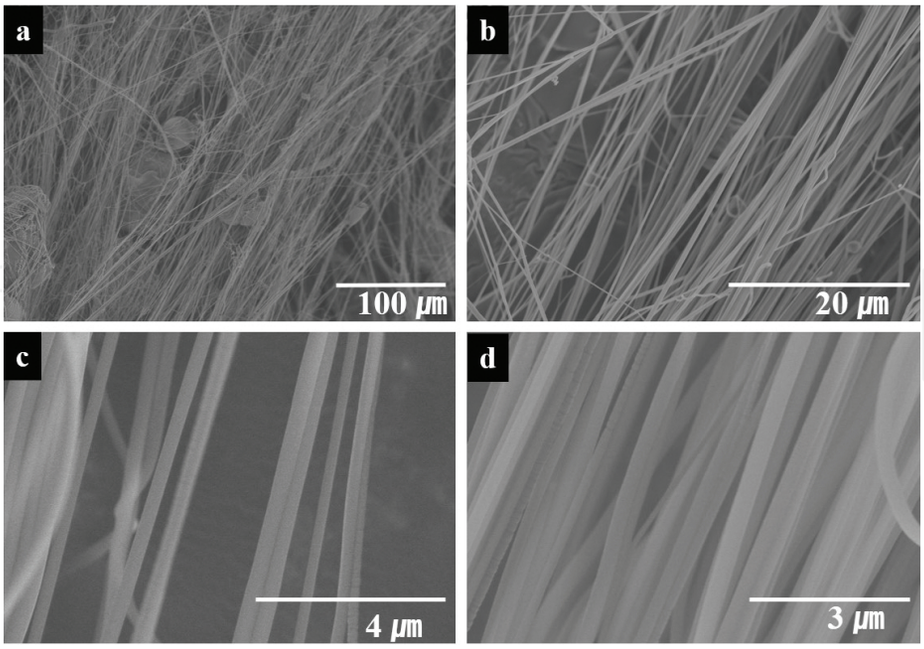

Figure 16. FE-SEM pictures of aligned nanofiber prepared by centrifugal jet electrospinning method. (Images b, c, and d are magnified form of image a.) (PVA solution concentration = 5 wt.%, TCD = 15 cm, applied voltage = 15 kV, rotational velocity = and 5000 rpm).

4. Conclusion

The study was aimed to apply a modified collector composed of two parallel vertical plates, and a twister-added collector to prepare highly aligned PVA nanofiber and its yarn, respectively. The result showed that this process was facile to prepare highly aligned PVA nanofiber and its yarn. In addition, a good reproducibility could be gained. The diameter and arrangement of the electrospun PVA-aligned nanofibers and its yarn were characterized using FE-SEM. For PVA-aligned nanofiber, we also studied the effect of voltage on alignment rate, melting temperature, and crystallinity. The results showed melting temperature and crystallinity increase gradually as the applied voltage increased, and the maximum degree of alignment was achieved at applied voltage 20 kV. On the other hand, for PVA yarn, effect of applied voltage and rotational velocity of twister on nanofiber alignment rate were examined and found that applied voltage 16 kV and rotational velocity 150 rpm are favorable conditions for getting highly aligned yarn. In addition, the effect of rotational velocity on diameter distribution and morphology of PVA nanofiber were also tested. The FE-SEM photographs revealed that smooth, well aligned, and bead free with good control on fiber diameter were obtained at the rotational velocity of 150 rpm. Beside aligned ultrafine PVA nanofibers have also been successfully assembled. The results indicated that centrifugal electrospinning is a competent technique to assemble highly aligned ultrafine PVA nanofibers which have a great prospective to use in electronic and optoelectronic devices.

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