

# HIGHLY ALIGNED FIBERS – A REVIEW OF MECHANICAL PROPERTIES AND APPLICATIONS AS A FILTER MEMBRANE

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## ABSTRACT

*Electrospun filter membranes show a high surface area to volume ratio and high porosity leading to a wide range of applications. The properties of electrospun membranes depend on the polymer properties such as molecular weight, viscosity, and polymer concentration, and membrane properties such as fiber diameter, and thickness of the membrane. One of the less studied factors that influence electrospun membranes is fiber alignment. Electrospun fibers typically have a random orientation of the fibers. The random orientation of the fibers weakens the mechanical strength of the membrane limiting the applications of the membranes. A few approaches to increase the mechanical strength of the membrane are by producing aligned fibers. In this review paper, different approaches to fabricating highly aligned electrospun fibers are presented.*

**Keywords:** Fibers, Membrane, Aligned Fibers

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## 1. INTRODUCTION

The electrospinning process [1-3] produces micro or nano sized fibers by randomly collecting charged jets of fibers onto a ground collector surface. The electrospun nanofiber membrane has a high surface area to volume ratio and high porosity. The electrospun nanofiber has reasonable mechanical strength for some applications. By applying a high voltage DC power supply to the tip of the needle, the polymer solution is charged and forms a Taylor cone at the tip to launch the polymer jets. These charged polymer jets are collected onto the ground collector surface placed at a certain distance from the tip of the needle. The resulting fiber membrane has a wide range of applications in [4,5] filtration, biomedical, drug delivery systems, material reinforcement, energy storage, protective clothing applications and food-based applications.

Filter membranes typically made up of electrospun fibers have interconnected pores with weak mechanical strength due to the small fiber diameter, and random alignment of fibers [5]. The random orientation of the fibers and low basis weight results in a relatively low mechanical strength. Stretching of the electrospun membrane may or may not orient the fibers due to the interconnected fiber structure formed during electrospinning process. Due to the interconnected fibers many of the fibers that were randomly oriented may or may not orient in the direction of the stretch resulting in no stretch of the fibers. Instead of stretching, the fibers may re-position relative to each other during the stretching process. Hence, stretching of the filter membrane may not be ideal to align the fibers in one direction. To improve the alignment of the fiber filter membrane, ideally, the fibers should be aligned during the electrospinning process to form aligned fibers or fiber yarn instead of randomly oriented fiber membranes. This allows for the fibers to orient along the yarn axis resulting in a highly aligned fiber membrane. This work explores the formation of highly aligned fibers using various collector surfaces during the electrospinning process.

## 2. METHODS OF PRODUCING HIGHLY ALIGNED FIBER MEMBRANE

Polymeric materials [6-9], such as Polypropylene (PP), Polyacrylonitrile (PAN), Polystyrene (PS), Polyethylene oxide (PEO) and various piezoelectric polymer materials such as PVDF and polyamides have been successfully electrospun to produce a fibrous membrane. Polymeric materials due to their high flexibility, tractable processing, good chemical stability, and readily tunable properties make it attractive for many applications.

### 2.1. Collectors

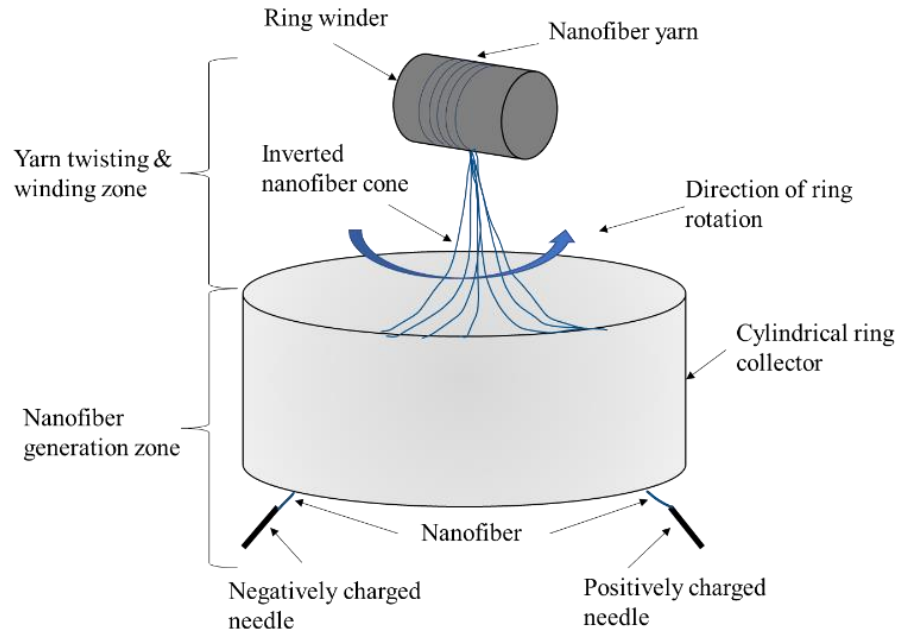
Researchers have studied various approaches to producing continuous and aligned nanofibers [10-12]. One of the primary factors studied to increase fiber alignment during the electrospinning process is to manipulate the electric field by changing the collector geometry. In the next few sections, a brief review is presented on various collector surfaces, resulting in electric field variation and the impact on the mechanical properties of the produced fiber membrane. The progress in electrospinning techniques for the production and construction of various nanofiber assemblies was studied by Teo et al [13]. Researchers have studied several approaches [14-19] to control the deposition and to obtain continuous electrospun nanofibers.

#### 2.1.1. Ring and Disc Collector

Two oppositely charged needles were used by Wu et al [20] to collect the fibers on a grounded metal disc. The fibers from the metal disc and rotating metal disc are collected to produce a twisted nanofiber yarn that showed a yarn diameter of 52 to 105 $\mu$ m with mechanical properties were 9.1cN/tex ideal for applications in composites and tissue engineering. Wu et al, highlight the point of further increasing the mechanical strength by increasing the twist in the yarn.

Shuakat et al [21] use a novel ring collector with two oppositely charged nozzles to generate a PVDF-HFP based nanofiber yarn as shown in Figure 2.1. The resulting nanofiber yarn had an average yarn diameter of 98 to 104 $\mu$ m, and the nanofibers had an average fiber diameter of 180nm to 270nm. The resulting tensile strength of the fiber yarn was 51.4MPa, exceeding the tensile strength of the nanofiber web (38MPa) produced using needle electrospinning using the same solution.

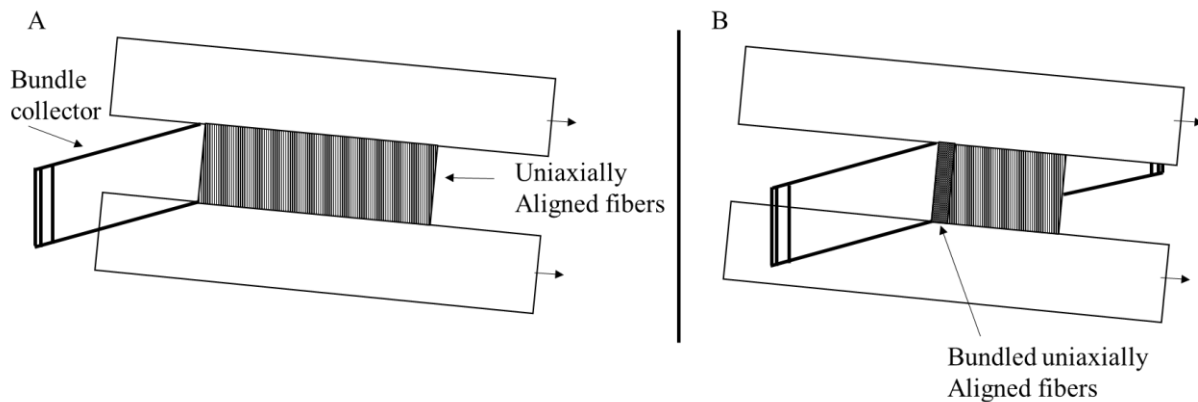
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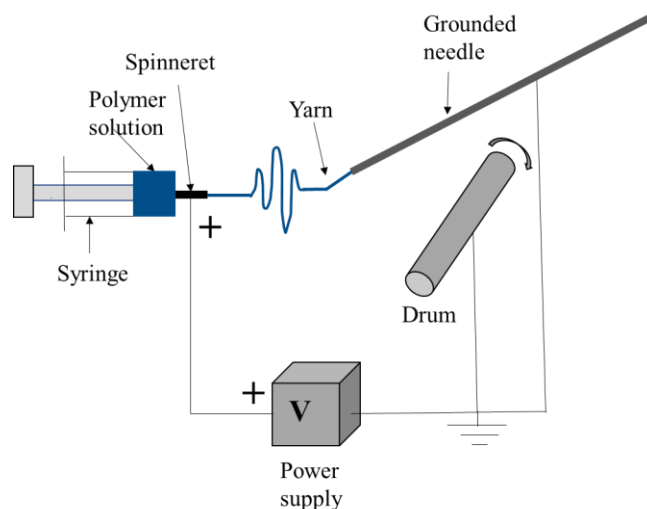
**Figure 2-1.** PVDF-HFP based polymer nanofiber production using a ring collector [21].

## 2.1.2. Bundle collector

PVDF – TrFE yarns were produced via twisting electrospun ribbons by Baniasadi et al [22]. The twisted yarns were stretched at 740% strain to produce a polymer coil that exhibited remarkable energy to failure of up to 98J/g. The twisting process was observed to increase the overall strength and toughness of the fabricated coil and yarns.



**Figure 2-2.** Illustration showing a) the bundle collector placed vertically, b) the bundle collector was moved across to collect the uniaxially aligned nanofibers [23].



**Figure 2-3.** Illustration of the self-bundling electrospinning setup for polymer fiber yarn [24].

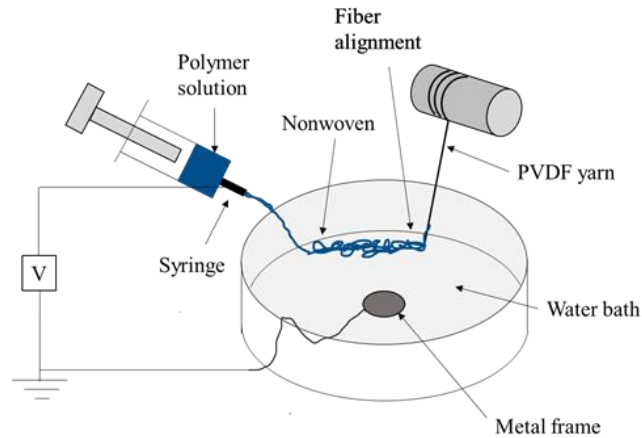
Uniaxially aligned electrospun PAN nanofibers were produced by Jalili et al [23], using electrically conductive substrates separated by a gap. The PAN nanofibers with a polymer concentration of 10wt% had a fiber diameter of  $165\pm 25\text{nm}$ . After a post-treatment process, the tensile strength improved from  $99\pm 12\text{MPa}$  to  $178\pm 15\text{MPa}$ . Wang et al [24] used a grounded needle tip to induce the self-bundling of the polymer nanofibers.

### 2.1.3. Liquid support collector

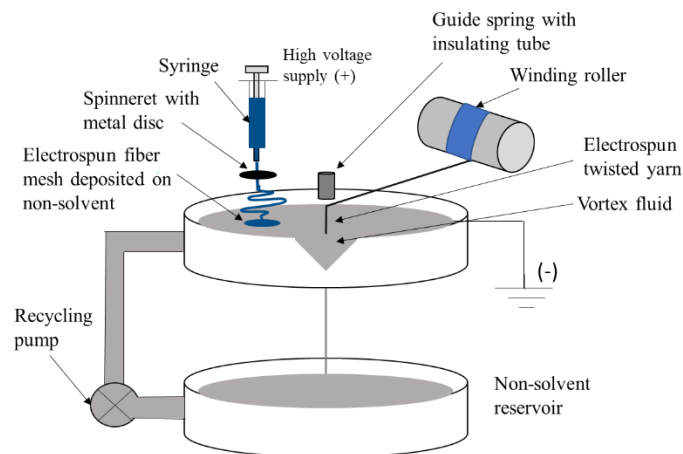
Baji et al [25] discussed an approach using a water bath as a collector surface to collect a well-aligned and self-assembled PVDF fiber yarn as shown in Figure 2-4. A 17% improvement in the tensile properties and a 41% increase in the strength of the fibers were observed by stretching the produced fiber yarn at  $100^\circ\text{C}$  and annealing. The post-treatment step increased the crystallinity and  $\beta$  crystalline phase in the fiber yarn.

Nartetamrongsutt et al [26] studied the production of twisted PAN fiber yarn using a metal disc and liquid support system. Figure 2-5 shows a continuous twisted PAN nanofibrous yarn production using a liquid support system by the formation of a vortex as discussed by Yousefzadeh et al [27]. The process of fiber yarn production showed more alignment of the fibers in the yarn without any yarn breakage and showed the capability to twist the fiber yarn in a single stage. The solvent flow velocity and the winding roller velocity were the major parameters driving the nanofiber alignment. The electrospun yarn had a diameter of  $96.69\pm 4.5\mu\text{m}$  and an average fiber diameter of  $1702.5\pm 0.6\text{nm}$ .

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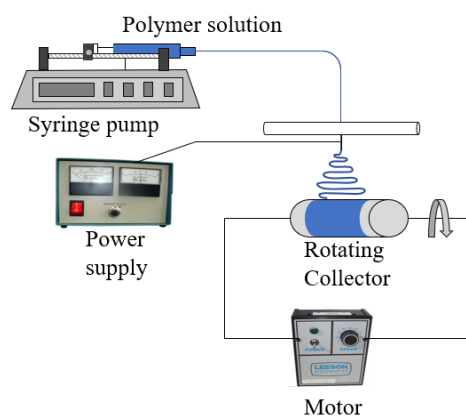


**Figure 2-4.** Schematic showing the production of PVDF fiber yarn using a water bath as a collector surface [25].



**Figure 2-5.** Fabrication of continuous twisted PAN fiber yarn production using a liquid support system [26].

### 2.13. Rotating drum collector



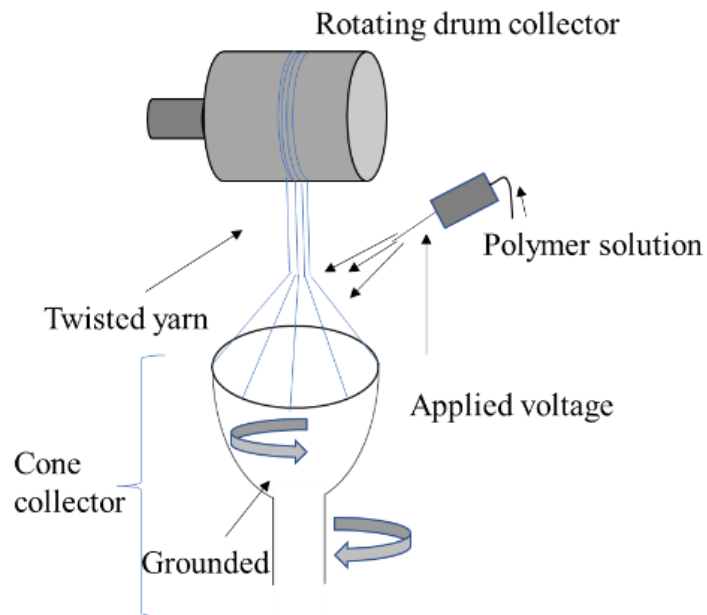
**Figure 2.6.** Illustration of the electrospinning setup [8].

Figure 2.6 shows an electrospinning setup with a rotating drum collector. The charged polymer jets are collected onto the ground rotating drum creating alignment of fibers along the lateral surface of the cylinder. Katta et al [6] electrospun nylon nanofiber as collected on the copper wire, SEM images after 5min of spinning time and 15min of spinning time showed a parallel arrangement of fibers. The parallel arrangement of the fibers allows for unique electrical, optical, and mechanical properties. Gade et al [8]

#### 2.1.4. Funnel collectors

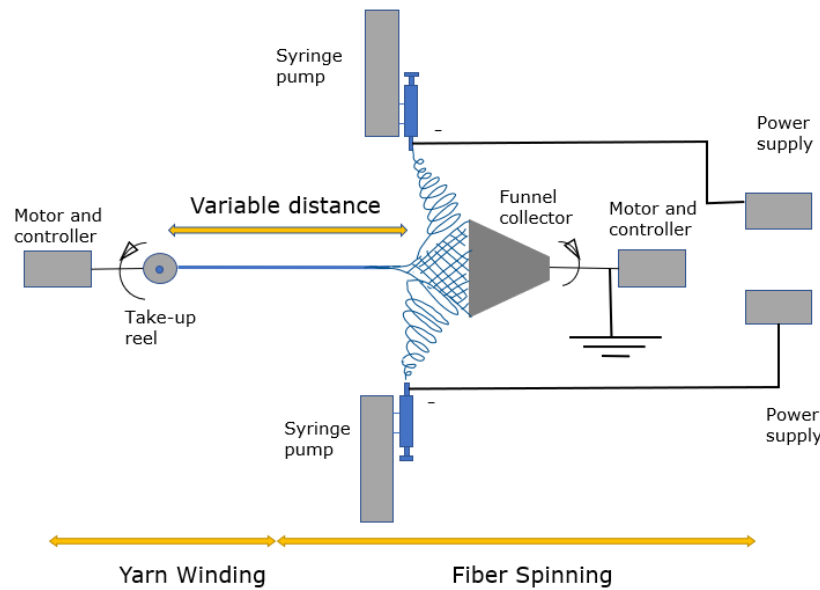
Ali et al [28], used oppositely charged nozzles to produce electrospun nanofibers that were collected on the surface of the funnel collector. The funnel rotation speed and yarn withdrawal rate determine the maximum yarn production rate, twist level, and fiber orientation. Ali et al [29], studied the electrospinning process using a sprocket disk. A comparison of the disk spinneret with and without a sprocket on the edge showed that the sprocket disk showed more uniform nanofibers with a small fiber diameter of  $356 \pm 86\text{nm}$  to that of  $429 \pm 114\text{nm}$  for the disk spinneret.

Production of nanofiber yarns has gained attention as they show significant improvement in the alignment of nanofibers and the mechanical properties by making some design modifications to the electrospinning setup. Such approaches have been discussed by Afifi et al, He et al, and Bokka et al [30, 31,14].



**Figure 2-7.** Illustration of electrospun Poly(lactic acid) (PLA) fibers as they were collected on the funnel surface [30].

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**Figure 2-8.** Formation of fiber yarn using oppositely charged needles [14].

Afifi et al [30], discussed the process of collecting PLA electrospun fibers into a web on the funnel surface and were drawn and guided into a winder to form a bundle as shown in Figure 2-7. SEM images of the twisted filament bundle drawn at 80°C to the ratio of 4 and 5, these fiber bundles, showed an average diameter of  $6.0 \pm 1.9$ mm. Due to molecular orientation, the resulting fiber bundle showed improved tensile properties.

Bokka et al [14] studied the formation of PVDF fiber yarns using a rotating funnel collector. The resulting fiber yarns had parallel stacked fibers that are twisted to produce a twisted fiber yarn. The PVDF fiber yarns had high fiber alignment compared to the randomly oriented fibers produced using a rotating drum collector. Due to the high fiber alignment, the produced PVDF fiber yarn showed a high charge per unit mass compared to the non-aligned fiber membrane. The aligned fiber yarns showed a yarn diameter of  $250\mu\text{m} \pm 50\mu\text{m}$  diameter yarn, with an average diameter of  $393\text{nm} \pm 213\text{nm}$ .

The influencing parameters are the degree of fiber alignment, twist induced, structure, and size of the collector surface. Of all the collector surfaces discussed, the funnel collector had the highest alignment of the fibers with reduced fiber diameter resulting in a fiber yarn that can be used for various fiber membrane applications. Funnel collector also resulted in the continuous fiber production ideal for large-scale production of the highly aligned fiber membrane.

### 2.3. Applications of electrospun yarns

Electrospun yarns have a wide range of applications due to the high surface area to the volume ratio. They can be used in Biomedical applications for wound dressing, and drug delivery systems. In tissue engineering electrospun fiber membranes are increasingly used as scaffolds. Filtration has been one of the most widely used areas for electrospun yarns as it is extensively used in filter membrane fabrication for air filtration applications. Other industries where electrospun yarns are widely used include Energy, sensors, and biotechnology.

With recent advancements in technology, electrospun yarns are being used in lithium batteries, as optical sensors and composite materials. Because of the high surface area to mass or volume, the electrospun fibers can be applied to many applications [32-37] such as filtration, composite materials, and biomedical applications including drug delivery, tissue engineering, and wound dressing.

## CONCLUSION

The development of aligned electrospun fiber membranes is highly desired for some filtration and biomedical applications. The surface to collect the electrospun fibers is critical to control the fiber membrane properties. It determines the alignment of the fibers, mechanical strength of the membrane, and filtration properties. Collector surfaces such as rings, discs, parallel-spaced substrates, liquid support systems, rotating drums, and needle collectors produce fibers that have twisted fibers and low to medium fiber alignment resulting in weaker mechanical strength, restricting the membrane applications. Challenges also exist to produce aligned continuous fibers. Using a funnel collector, the continuously aligned fibers are produced with high mechanical strength. The produced aligned fibers can be potentially used as a filter membrane in filtration applications.

## REFERENCES

- [1] Xue, J.; Wu, T.; Dai, Y.; Xia, Y. Electrospinning and electrospun nanofibers: methods, materials, and applications. *Chemical Reviews* **2019**, 119, vol 8, 5298-5415.
- [2] Sundarajan, S.; Tan, K.L.; Lim, S.H.; Ramakrishna, S. Electrospun nanofibers for air filtration applications. *Procedia Engineering* **2014**, vol 75, 159 – 163.
- [3] Persano, L.; Camposeo, A.; Tekmen, C.; Pisignano, D. Industrial upscaling of electrospinning and applications of polymer nanofibers: A review. *Macromolecular Materials and Engineering* **2013**, vol 298, 504 – 520.
- [4] Fang, J.; Niu, H.; Tong, L.; Wang, X. Applications of electrospun nanofibers. *Chinese Science Bulletin* **2008**, vol 53, no 15, 2265-2286.
- [5] Bhardwaj, N; Kundu, S.C. Electrospinning: A fascinating fiber fabrication technique. Research review paper, Elsevier, *Biotechnology Advances* **2010**, vol 28, 325 – 347.
- [6] Katta, P; Alessandro, M; Ramsier, R. D; Chase, G. G. Continuous electrospinning of aligned polymer nanofiber onto a wire drum collector. *Nano Letters* **2004**, vol 4, No 11, 2215 – 2218.
- [7] Reneker, D. H; Chun, I. Nanometer diameter fibers of polymer produced by electrospinning. *Nanotechnology* **7.3** **1996**, 7.3 vol 216.
- [8] Gade, Harshal, Sreevalli Bokka, and George G. Chase. Polarization treatments of electrospun PVDF fiber mats. *Polymer* **2012**, vol 212, 123152.
- [9] Li, D.; Wang, Y.; Xia, Y.; Electrospinning of polymeric and ceramic nanofibers as uniaxially aligned arrays. *Nano letters* **2003**, vol 3, no.8, 1167-1171.
- [10] Mikhailov, G. P. Dielectric losses and polarization of polymers. *Journal of Polymer Science* **1958**, 605-614. Prague symposium.
- [11] Sessler, G. M.; Gerhard-Multhaupt, R. Charge and polarization profiles in polymer electrets. *IEEE Transactions on electrical insulation* **1986**, vol. EI-21, no.3.
- [12] Jayesh Doshi, Darrell H. Reneker. Electrospinning process and applications of electrospun fibers. *Journal of Electrostatics* **1995**, vol 35, Issue 2-3, 151-160.
- [13] Teo, W. E; Inai, R; Ramakrishna, S. Technological advances in electrospinning of nanofibers. *Science and Technology of advanced materials* **2011**, vol 12, 013002.

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- [14] Bokka, Sreevalli, Yue Li, Darrell H. Reneker, and George G. Chase. Achievement of high surface charge in poly (vinylidene fluoride) fiber yarns through dipole orientation during fabrication. *Journal of Applied Polymer Science* **2023**, vol 140, no. 1, e53265.
- [15] Sahay, R; Thavasi, V; Ramakrishna, S. Design modifications in electrospinning setup for advanced applications. *Journal of nanomaterials* **2011**, Article ID 317673, 17 pages.
- [16] Baji, A; Mai, Y-W; Wong, S-C; Abtahi, M; Chen, P. Electrospinning of polymer nanofibers: Effects on oriented morphology, structures and tensile properties. *Composites Science and Technology* **2010**, vol 70, 703 – 718.
- [17] Firyach -Nowacka, A; Snoika, K; Wiak, S; Gliscinska, E; Krucinska, I; Chrzanowski, M. 3-Dimensional computer model of electrospinning multicapillary unit used for electrostatic field analysis. *Open Physics* **2017**, vol 15, 1049 – 1054.
- [18] Dabirian, F; Hosseini, F. Y; Hosseini Ravandi, S. S. Manipulation of the electric field of electrospinning system to produce polyacrylonitrile nanofiber yarn. *Journal of Textile Institute* **2007**, vol 98, no 3, pp 237 – 241.
- [19] Shin, Y. M; Hohman, M. M; Brenner, M.P; Rutledge, G. C. Experimental characterization of electrospinning: the electrically forced jet and instabilities. *Polymer* **2001**, vol 42, 9955-9967.
- [20] Wu, S-H; Qin, X-H. Uniaxially aligned Polyacrylonitrile nanofiber yarns prepared by a novel electrospinning method. *Materials Letters* **2013**, 106, 204-207.
- [21] Shuakat, M. N; Wang, X; Lin, T. Electrospinning of nanofiber yarns using a novel ring collector. *Proceedings of the 2013 Fiber Society Spring Conference*, Fiber Society, Geelong, Vic, pp 238 – 239.
- [22] Baniyasi, M; Huang, J; Xu, Z; Moreno, S; Yang, X; Chang, J; Quevedo–Lopez, M. A; Naraghi, M; Minary-Jolandan, M. High-performance coils and yarns of polymeric piezoelectric nanofibers. *ACS Applied Materials and Interfaces* **2015**, vol 7, 5358 – 5366.
- [23] Jalili, R; Morshed, M; Hosseini-Ravandi, S. A. Fundamental parameters affecting electrospinning of PAN nanofibers as uniaxially aligned fibers, *Journal of Applied Polymer Science* **2006**, vol 101, 4350-4357.
- [24] Wang, X; Zhang, K; Zhu, M; Yu, H; Zhou, Z; Chen, Y; Hsiao, B. S. Continuous polymer nanofiber yarns prepared by self-bundling electrospinning method, *Polymer* **2008**, 49, 2755-2761.
- [25] Baji, A; Mai, Y. W; Du, X; Wong, S-C. Improved tensile strength and ferroelectric phase content of self-assembled polyvinylidene fluoride fiber yarns, *Macromolecular Material Engineering* **2012**, 297, 209 – 213.
- [26] Nartetamrongsutt, K. Modification of electrospinning solutions and yarn production for filtration application, *Dissertation* **2013**, The University of Akron.
- [27] Yousefzadeh, M; Latifi, M; Teo, W. E; Amani–Tehran, M; Ramakrishna, S. Producing continuous twisted yarn from well – Aligned nanofibers by water vortex. *Polymer engineering and science* **2011**, 323 – 329, DOI:10.1002/pen2 1800.
- [28] Ali, U; Wang, X; Lin, T. Direct electrospinning of nanofiber yarns, *Peer reviewed research, AATCC REVIEW March/APRIL* **2013**, 57-63.
- [29] Ali, U; Niu, H; Aslam, S; Jabbar, A; Rajput, A. W; Lin, T. Needleless electrospinning using sprocket wheel disk spinneret. *Journal of Material Science* **2017**, 52, 7567 – 7577.
- [30] Afifi, A. M; Nakano, S; Yamane, H; Kimura, Y. Electrospinning of continuous aligning yarns with a funnel target. *Macromolecular Material Engineering* **2010**, 295, 660-665.
- [31] He, J.X.; Qi, K.; Zhou, Y.M.; Cui, S.Z. Fabrication of continuous nanofiber yarn using novel multi-nozzle bubble electrospinning. *Polymer International* **2014**, vol 63, issue 7, 1288 – 1294.

- [32] Brown, R. C. Air filtration: an integrated approach to the theory and applications of fibrous filters. 1<sup>st</sup> ed; Pergamon Press, New York, USA, **1993**.
- [33] Sofi, H. S.; Ashraf, R.; Khan, A. H.; Mushtaq, A. Beigh, Shafaquat Majeed, Faheem A, Sheikh, Reconstructing nanofibers from natural polymers using surface functionalization approaches for applications in tissue engineering, drug delivery and biosensing devices, Materials Science and Engineering C **2019**, vol 94, 1102-1124.
- [34] Haider, A.; Haideer, S.; Kang, I-K. A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and biotechnology, Arabian Journal of Chemistry **2018**, vol 11, 1165-1188.
- [35] Kenry, Chwee Teck Lim. Nnaofiber technology: current status and emerging developments. Progress in Polymer Science **2017**, vol 70, 1-17.
- [36] Jeong F. Kim, Ji Hoon Kim, Young Moo Lee, Enrico Drioli. Thermally induces phase separation and electrospinning methods for emerging membrane applications: A review. Advances in Materials. Separations: Materials, Devices and Processes **2016**, vol. 62, no 2, 461-490.
- [37] Farah Ejaz Ahmed, Boor Singh Lalia, Raed Hashaikeh. A review on electrospinning for membrane fabrication: Challenges and applications. Desalination **2015**, vol. 356, 15-30.

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