# PRODUCTION OF NANOFIBERS USING ELECTROSPINNING WITH THE USE OF METAL LAMS

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## ABSTRACT

This study presents a novel design for an industrial electrospinning system aimed at the large-scale production of nanofibrous materials. The proposed system utilizes electrospinning of a polymer solution or melt within a high-intensity electric field generated between the collection electrodes and the polymer solution or melt deposited on the spinning apparatus. The developed machine is designed to achieve performance comparable to or exceeding that of existing electrospinning devices. In its basic configuration, the system operates with a single spinning head and a single collecting electrode. However, the design allows for scalability, accommodating up to six spinning heads and six corresponding collecting electrodes, thereby significantly enhancing production efficiency. Furthermore, the modular design enables flexible operation, allowing for the selective use of spinning heads to adapt to varying production demands. This adaptability, along with the capacity for customization, distinguishes the proposed system from existing technologies, making it suitable for both industrial applications and research-oriented modifications.

## KEYWORDS

Nanofibers; Needle-less; Electrospinning; Production.

## INTRODUCTION

Nanofibers have gained significant attention due to their unique properties, including a high surface-area-to-volume ratio, tunable porosity, and exceptional versatility in biomedical, filtration, and textile applications. These ultrafine fibers provide an excellent platform for drug delivery, wound healing, air and liquid filtration, and protective textiles due to their ability to mimic the extracellular matrix, provide high permeability, and support controlled release of active agents [1,2]. The growing interest in nanofibers has led to the development of various fabrication methods, each relying on distinct physical and chemical principles, including phase separation, template synthesis, self-assembly, and electrospinning [3]. Among these, electrospinning has emerged as the most effective and scalable technique, allowing for the continuous production of nanofibers with controlled morphology and tailored properties. This method utilizes a high-voltage electric field to transform a polymer solution or melt into ultrafine fibers, which solidify upon solvent evaporation or cooling [4,5].

Electrospinning has a long and well-documented history, with the first patent dating back to 1902 by J.F. Cooley [6], followed by subsequent refinements by Formhals in the 1930s. Despite its early discovery, electrospinning gained widespread recognition only in the late 20th century due to advances in nanotechnology and materials science [7]. The fundamental process of electrospinning involves the application of an external electric field to a polymer solution or melt, generating a charged polymer jet at the Taylor cone. As the solvent evaporates, the polymer solidifies into continuous nanofibers, which are deposited onto a collector. The properties of the resulting nanofibers are influenced by multiple interdependent parameters, including polymer solution characteristics (e.g., viscosity, concentration, surface tension, dielectric properties), processing factors (e.g., applied voltage, flow rate, electrode geometry, collection distance), and environmental conditions (e.g., humidity, temperature, airflow) [8–13]. Almetwally et al. [19] provided a comprehensive review of nanofiber production parameters and their impact on fiber morphology. Their study emphasized the importance of precise control over polymer solution properties and processing conditions to achieve uniform nanofiber structures. Understanding and optimizing these parameters is critical for producing nanofibers with consistent diameters,

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mechanical integrity, and application-specific properties.

Among the various electrospinning configurations, needle-based electrospinning remains widely used in laboratory research due to its ability to produce well-defined fibers. However, its limited production rate and susceptibility to clogging restrict its industrial scalability [14]. To address these limitations, needle-less electrospinning has emerged as a highly efficient alternative for large-scale fiber production. In this technique, a high-voltage electric field acts on a polymer solution or melt distributed over a rotating spinning electrode, such as a cylinder, disk, or wire array [15,16]. Unlike traditional needle-based electrospinning, needle-less techniques enable the simultaneous formation of multiple Taylor cones along the electrode's surface, significantly increasing productivity.

One of the key challenges associated with needle-less electrospinning, however, is the inability of the spinning electrode to effectively mix the polymer solution within the reservoir. Unlike needle-based setups where fresh polymer solution is continuously supplied via a syringe pump, needle-less electrospinning relies on a bulk reservoir that is exposed to prolonged processing times. Due to the low rotational speed of the spinning electrode (typically a few revolutions per minute) and its limited dimensions, the polymer solution undergoes gradual thickening, solvent evaporation, and potential chemical degradation. As a result, the viscosity of the solution increases over time, leading to fiber diameter inconsistencies, reduced spinning efficiency, and eventual process failure. This issue is particularly problematic for high-molecular-weight polymers and volatile solvents, which exacerbate solution instability.

To overcome this limitation, various mixing strategies have been proposed. For instance, Wei et al. [17] developed a needle-less electrospinning system incorporating a cylindrical collecting electrode, achieving a maximum nanofiber productivity of 4.5 g/hour. Their study demonstrated that fiber diameter increased proportionally with polymer concentration, and the produced nanofibers exhibited promising filtration performance. However, the lack of active solution mixing resulted in polymer thickening over time, affecting long-term stability. Similarly, Kim et al. [18] designed an air-jet electrospinning spinneret to enhance fiber uniformity in thermoplastic and thermoset polymer nanofibers. While effective for specific polymer systems, this approach did not address the fundamental issue of solution homogeneity in needle-less electrospinning. Furthermore, Bryner et al. [20] patented an improved electrospinning process in which voltage was directly applied to a pair of electrodes placed parallel to a grounded spinneret, overcoming disadvantages associated with conventional voltage application methods. These studies collectively highlight the need for optimized electrospinning systems that balance productivity, fiber quality, and process stability.

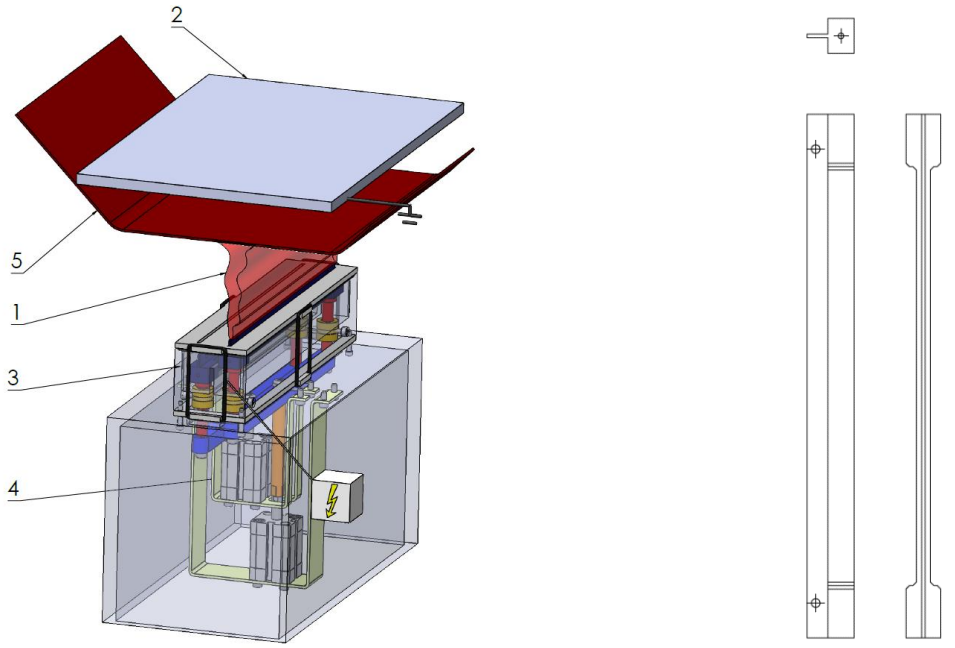
Despite these advancements, a significant gap remains in addressing polymer solution thickening and degradation during extended needle-less electrospinning processes. Conventional mixing solutions, such as the integration of mechanical stirrers or ultrasonic agitation, introduce additional complexity, increase energy consumption, and require larger reservoirs to prevent interference with the spinning electrode. For example, the introduction of a moving auger within the polymer reservoir, as proposed in [21], successfully enhanced solution homogeneity but required additional mechanical components, increasing system complexity and costs.

This study aims to address the challenges associated with solution homogeneity in needle-less electrospinning by developing a novel mixing strategy that ensures consistent polymer solution properties without compromising process efficiency. The proposed approach is evaluated in terms of its impact on fiber morphology, productivity, and overall electrospinning performance. By optimizing solution stability, the operational lifespan of needle-less electrospinning setups can be extended, enabling the production of uniform, high-quality nanofibers suitable for industrial applications. Addressing one of the key limitations of current needle-less electrospinning systems, this research contributes to the advancement of scalable electrospinning technologies, supporting their broader adoption in biomedical engineering, filtration systems, and functional textiles. The findings offer valuable insights into improving nanofiber manufacturing processes, facilitating the transition from laboratory-scale research to large-scale commercial production.

## EXPERIMENTAL PART

### Design and construction of novel electrospinning device

Based on the principles of various spinning technologies previously outlined, a specialized electrospinning agent has been designed to ensure full coverage of the substrate's width, which is typically 1600 mm in industrial-scale operations. The spinning agent is designed to operate within a container filled with a polymer solution or melt. One of the most advantageous features of this design is the use of a bar, as illustrated in Fig. 1(b), which shows the shape of the bar used in the proposed device. The upper edge of the bar is utilized to create a Taylor cone (Fig. 2). Additionally, the bar's horizontal, rectilinear motion helps mix the polymer solution or melt, preventing degradation and ensuring extended usability of the polymer solution for




(a) (b)

**Figure 1.** Machine concept. (a) (1) emerging nanofibers, (b) grounded collector, capturing nanofibers, (3) polymer solution or melt in a container, (4) bars with drives, (5) substrate for nanofibers. (b) Bar shape used in the proposed device.

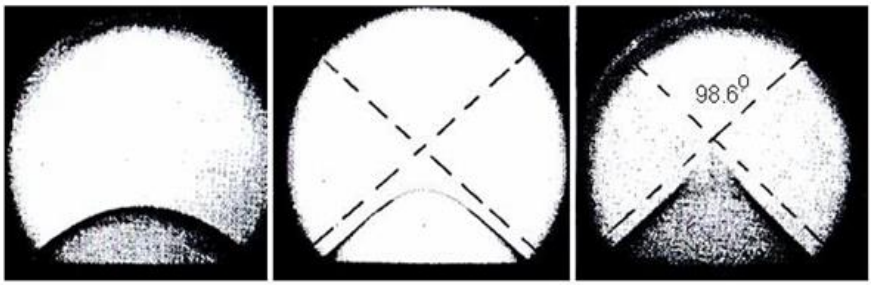


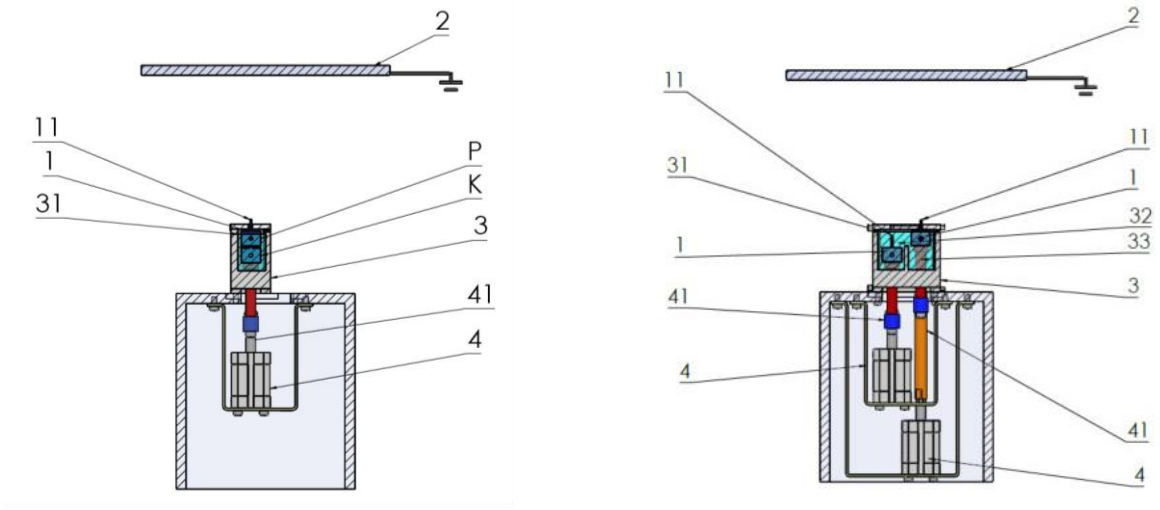

**Figure 2.** Taylor cone [7].

electrospinning. This dynamic motion contributes to the long-term stability of the polymer and ensures high-quality nanofiber production. The prototype of the device designed for electrospinning a polymer solution or melt is depicted in Fig. 1(a), where two spinning heads work in a rectilinear reciprocating motion within a container filled with the polymer solution. The design and operation of this system are optimized to facilitate efficient electrospinning for industrial-scale production.

Fig. 3 (a) provides a schematic cross-section of the electrospinning device equipped with a single spinner, while Fig. 3 (b) showcases the cross-section of a dual-spinning nanofiber production system utilizing the proposed device. The spinner is constructed from an electrically non-conductive material, in this case, stainless steel, with its upper edge positioned towards the collecting electrode, which is located above the spinner. The spinner can be adjusted in the solution reservoir between two distinct positions: the working position (represented by the dotted position P), where the edge of the spinner is closest to the collecting electrode, and the resting position (dotted position K), where the spinner is furthest from the electrode. The polymer solution is applied to the spinner in such a way that, in its resting position, the spinner is submerged below the surface of the polymer solution, ensuring an even coating of the polymer solution for optimal electrospinning. The spinner operates in a straightforward motion, with a pneumatic cylinder driving the movement of each spinner located below the magazine. The pneumatic cylinder activates the lifting mechanism, which must be perfectly sealed with a rubber gasket to prevent leakage as it moves through the polymer solution reservoir. The spinners are equipped with side holes, facilitating easy handling, removal, and storage.

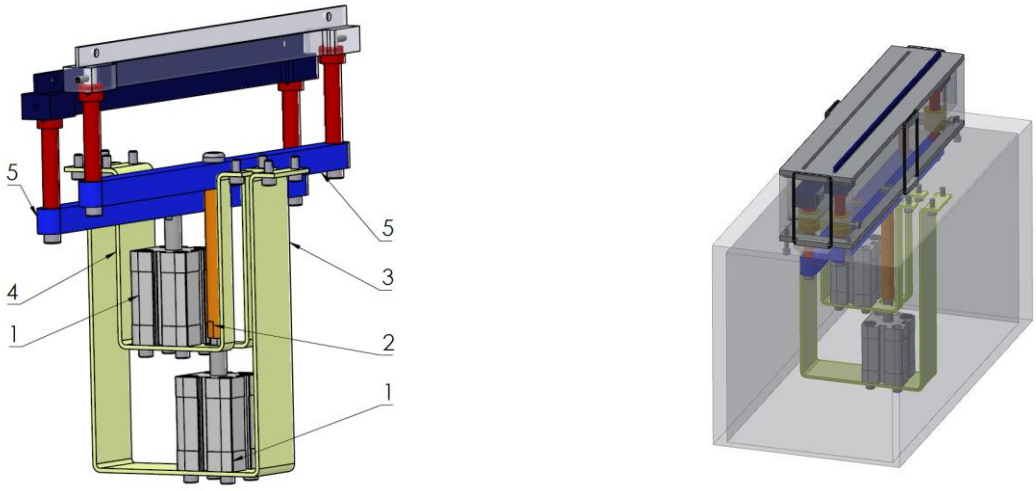
Tests demonstrated that the straight edge of the spinner was the most effective design, as it simplifies cleaning and ensures even distribution of the polymer solution. To maintain a consistent level of the polymer solution or melt, the solution reservoir is equipped with an inlet and outlet system (not shown), including an overflow mechanism. This system helps ensure the polymer solution remains at the optimal level throughout the electrospinning process.

During the electrospinning process, a high voltage of negative polarity is applied to the collecting electrode, while the polymer solution or melt is subjected to a high voltage of opposite polarity.




(a) (b)

**Figure 3.** Cross-section of the proposed device(s) with a (a) single spinner; and (b) with two spinners. (1) Spinners, (2) collection electrode, (3) polymer reservoir, (4) double-acting pneumatic motor, (11) edge of the spinneret, (31) polymer or melt level, (32) baffle, (33) ) polymer solution or melt, (41) movement mechanism, (P) working position, (K) rest position.




(a) (b)

**Figure 4.** (a) Motion gear with rails and tie rods fitted. (1) Pneumatic drive, (2) piston rod extension, (3) pneumatic drive mount, (4) pneumatic drive mount, (5) tie rod connecting piece. (b) View of the prototype of the machine itself.

As the polymer solution is drawn toward the spinner, the spinner moves to its working position under the influence of its drive system, bringing it closer to the collecting electrode. At this point, electrostatic forces induce the formation of Taylor cones at the tips of the polymer solution. The polymer solution is then elongated, forming nanofibers that are continuously deposited onto the surface of a flat substrate. Once a predetermined amount of polymer solution has been applied, and after a pre-set time interval, the spinner returns to its resting position, moving away from the collecting electrode. The cyclic movement of the spinner through the polymer solution not only ensures the uniform deposition of nanofibers but also facilitates the mixing of the polymer solution, enhancing the lifespan of the solution and minimizing the risk of chemical degradation.

After the spinner completes a cycle of deposition, the polymer solution or melt is refreshed, and the electrospinning process continues. This cyclical movement of the spinner, combined with the mixing of the polymer solution, results in enhanced solution stability and optimal nanofiber quality.

A functional prototype of the electrospinning device was assembled to verify the operational effectiveness of the design, as shown in Fig. 4(a). This prototype serves as the basis for trial production, and it is anticipated that the system will be integrated into the existing Nanospider. The completed machine, shown in Fig. 4(b), incorporates the key features necessary for large-scale electrospinning.

The final machine design will feature six spinning heads, allowing for simultaneous production from multiple spinners, enhancing the efficiency and scalability of the nanofiber manufacturing process. Fig. 5 presents an overall view of the intended design of the machine, highlighting the main components essential for the operation and control of the device. This design incorporates knowledge gained from the testing and evaluation of the prototype described

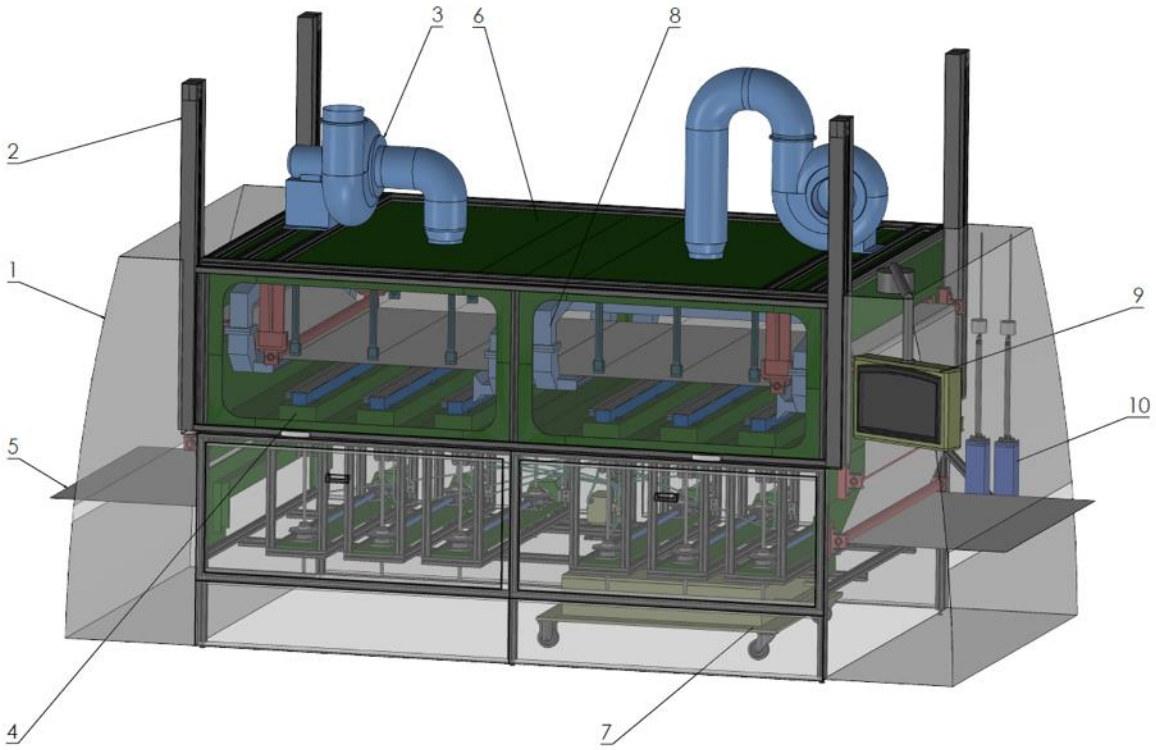



**Figure 5.** Machine concept. (1) Machine cover, (2) Machine frame, (3) Acid-proof fan, (4) Spinning head, (5) Base, (6) Spinning proctor, (7) Polymer distribution, (8) Ventilation, (9) Control panel, (10) dischargers.

earlier, excluding the electrical components, which will be addressed in subsequent studies. A more detailed description of the individual parts and components of the machine can be found in previous work on the subject [20].

The proposed device offers several advantages over conventional electrospinning methods, particularly in terms of solution handling and fiber deposition consistency. Traditional electrospinning systems often face challenges in maintaining uniform solution delivery and preventing polymer solution degradation. In contrast, the innovative spinner design in this system effectively addresses these issues by continuously mixing the polymer solution while ensuring stable electrospinning conditions. The dynamic, back-and-forth motion of the spinner facilitates even solution distribution across the spinning surface, minimizing the risk of solution pooling or degradation. This approach enhances fiber uniformity and improves overall process efficiency, making it a promising advancement for large-scale nanofiber production.

## Performance of the developed electrospinning device

To perform the electrospinning process, the polymer solution for producing polyamide nanofibrous layers was prepared by dissolving polyamide 9T. in a mixture of acetic and formic acid (56/34 v/v), yielding a 10% polymer solution. The solution was mixed for approximately 3 minutes using a magnetic stirrer to ensure a homogeneous distribution. Polyamide 9T was selected due to its long aliphatic chain consisting of nine methylene groups, which provide excellent thermal stability and low water absorption. This polymer was chosen to produce the nanofibrous layer, as it offers ease of fabrication and desirable properties for various applications. A spunbond nonwoven fabric with an area weight of 29 g/m² was used as the substrate. The prepared polymer solution was then added to the reservoir containing the spinning bars, and the solution was subjected to an electric field with a voltage of 69.5 kV. A condenser was positioned above the solution tray at a distance of 190 mm. The supporting base fabric was moved at a speed of 0.1 m/min to ensure uniform deposition of nanofibers. The areal weight of the resulting nanofibrous layers was 1 and 2 g/m². The morphology of the fabricated nanofibrous layers was evaluated using scanning electron microscopy (SEM), as shown in Fig. 6.

Image analysis revealed that the electrospun nanofibers exhibited an average fiber diameter of 715 ± 190 nm. Pore structure analysis indicated that the maximum Feret diameter of the pores reached 0.67 ± 0.3 µm, while the equivalent diameter of the pores was measured at 0.52 ± 0.25 µm. These values suggest a relatively uniform fiber morphology with a well-defined porous network, which is crucial for applications requiring controlled permeability, such as filtration, tissue engineering, and drug delivery. The observed variation in fiber diameter and pore size distribution can be attributed to factors such as

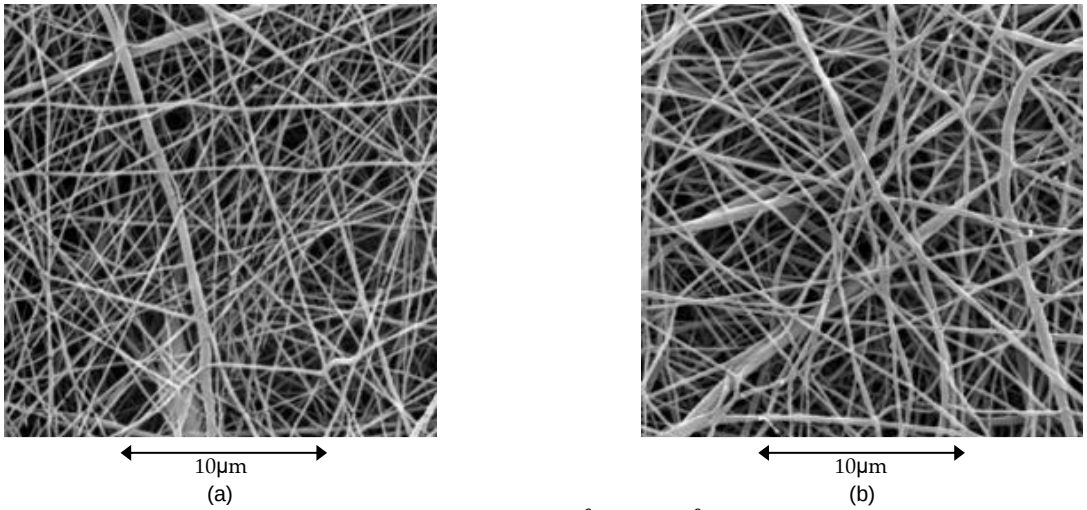



**Figure 6.** SEM of a nanofibrous membrane with areal weights: (a) 1 g.m$^{-2}$, (b) 2 g.m$^{-2}$.

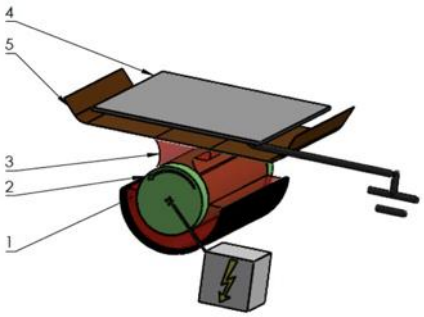



**Figure 7.** (1) Polymer solution or melt, (2) roller, high voltage source, (3) emerging nanofibers, (4) grounded collector, capturing nanofibers, (5) substrate for nanofibers.

polymer solution viscosity, electrospinning parameters, and environmental conditions during fabrication. Further optimization of processing conditions may help reduce variability and achieve even greater control over nanofiber dimensions and porosity.

To benchmark the proposed electrospinning system, its performance was compared to that of the Nanospider™ system, an industrial-scale nanofiber production technology. Developed by Prof. Jirsák at the Technical University in Liberec and manufactured by Elmarco (Czech Republic), Nanospider™ employs nozzle-free electrospinning. Instead of capillary nozzles, it utilizes a rotating cylinder or string partially immersed in a polymer solution (Fig. 7). As the cylinder rotates, a thin polymer film forms on its surface, where a high-voltage electric field induces Taylor cone formation, initiating electrospinning. This approach enables high-throughput production and makes Nanospider™ one of the most efficient needle-less electrospinning technologies.

Fig. 8 presents SEM images of nanofibrous layers produced by both systems at magnifications of 50× and 3000×, providing a visual comparison of fiber morphology and distribution. These results demonstrate that both technologies produce nanofibers with uniform diameters and pore structures.

A detailed image analysis was performed to compare the fiber morphology, pore structure, and uniformity of nanofibrous layers obtained from the Nanospider™ and the proposed device (Table 1). The results showed that the proposed system produced nanofibers with an average diameter of 715 ±190 nm, which is slightly larger than the 625 ±200 nm observed for the Nanospider™. The equivalent pore diameter was 0.52 ±0.25 µm for the proposed device and 0.56 ±0.30 µm for the Nanospider™. The maximum Feret diameter of the pores measured 0.67 ±0.30 µm for the proposed device, compared to 0.87 ±0.58 µm for the Nanospider™. The pore density per cm² was comparable between the two systems, with the proposed device producing 87.2 × 10⁶ pores/cm² and the Nanospider™ yielding 89.5 × 10⁶ pores/cm².

## DISCUSSION

Several industrial companies have developed scalable electrospinning technologies to overcome the limitations of traditional laboratory-scale methods. These advancements aim to enhance production efficiency, fiber uniformity, and adaptability to various material systems. One such company, SPUR a.s., has implemented multiple nanofiber production

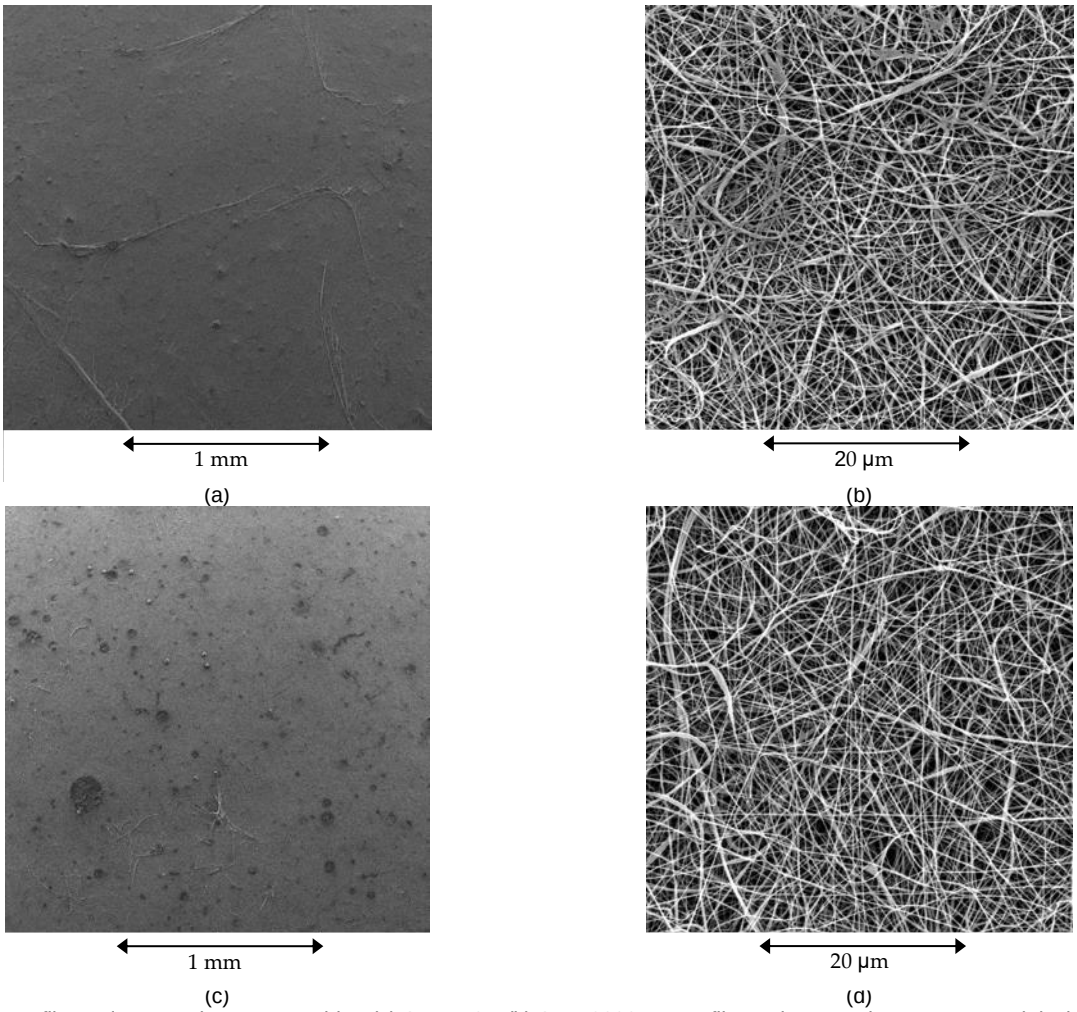



**Figure 8.** Nanofibrous layer made on Nanospider, (a) SEM, 50x, (b) SEM 3000x, Nanofibrous layer made on a proposed device (c) SEM, 50x, (d) SEM, 3000x.

**Table 1.** Evaluation of nanofibrous layers produced on Nanospider and proposed device.

| | | Number of pores [$cm^{-2}$] | Max Feret of pores [µm] | Eq. diam. of pores [µm] | Fiber diameter [nm] |
|---|---|---|---|---|---|
| Nanospider | Mean | 89563758 | 0.87 | 0.56 | 625 |
| | SD | 2526152 | 0.58 | 0.30 | 0.20 |
| Proposed device | Mean | 87235952 | 0.67 | 0.52 | 715 |
| | SD | 2052649 | 0.30 | 0.25 | 0.19 |

techniques, including electrostatic spinning, melt spinning, and electric blowing (Fig. 9). Each method offers distinct advantages depending on the target application, polymer compatibility, and scalability requirements Electrostatic spinning, similar to our approach, utilizes an electric field to generate nanofibers. Industrial-scale adaptations include multi-nozzle electrospinning for higher throughput and needleless/free-surface electrospinning, as seen in Nanospider™ technology. These modifications enhance scalability while maintaining fiber morphology and uniformity. Melt spinning, unlike solvent-based electrospinning, this technique relies on polymer melt extrusion, eliminating the need for volatile organic solvents. This improves environmental and safety profiles, making it a viable option for large-scale nanofiber production. However, it is restricted to thermoplastic polymers with appropriate melt viscosities, limiting material selection. Electric blowing, a hybrid method combining electrospinning with air-jet technology, increasing deposition rates. This approach improves throughput but requires careful optimization to prevent fiber defects, ensuring consistency in diameter distribution and surface properties. Compared to the scalable technologies employed by SPUR a.s., our proposed electrospinning system offers greater flexibility for solution-based fiber production, particularly in applications requiring precise fiber morphology, surface functionalization, and post-processing modifications. However, further optimization is necessary to achieve production rates comparable to SPUR a.s.'s industrial methods.

Beyond conventional electrospinning, several alternative nanofiber production techniques have been explored to improve scalability, efficiency, and

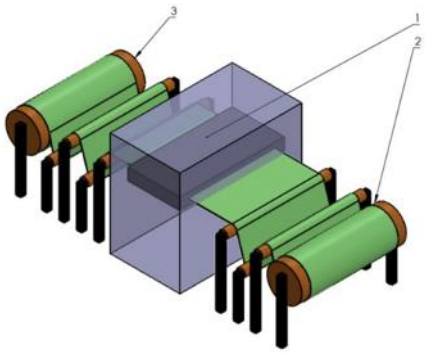
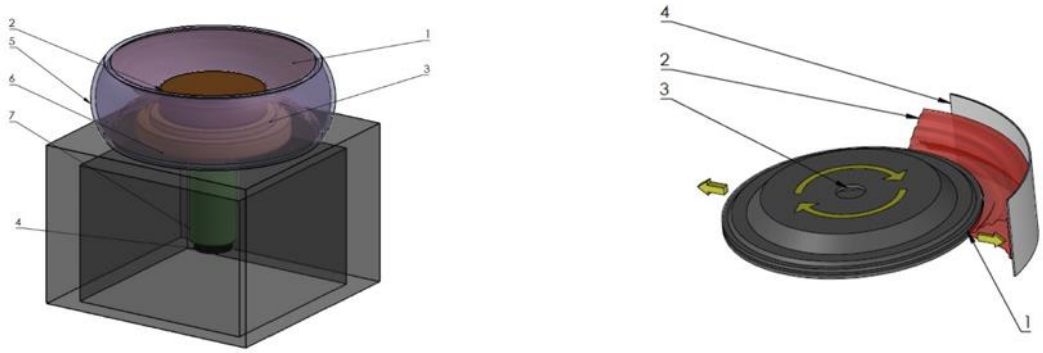



**Figure 9.** SPUR-line Spinning process: (1) spinning space, (2) winding, (3) unwinding.




(a) (b)

**Figure 10.** Force-spinning process. (a) (1) forming nanofiber, (2) spinneret, (3) furnace, (4) brake, (5) nanofiber catcher, (6) heater, (7) motor. (b) (1) opening, (2) forming nanofiber, (3) material supply, (4) nanofiber catcher.

material versatility. Two notable approaches are air-jet electrospinning and forcespinning, both of which offer advantages over traditional electrostatic methods. Air-Jet electrospinning integrates a high-velocity air stream into the electrospinning process, assisting in fiber elongation and deposition. By reducing reliance on strong electric fields, air-jet electrospinning enhances throughput and deposition uniformity while maintaining nanoscale fiber diameters. The process is particularly advantageous for high-speed production lines, making it a promising alternative for large-scale nanofiber manufacturing. Forcespinning (FibeRio Technology Corporation), unlike electrospinning, relies on electrostatic forces, forcespinning utilizes centrifugal force to draw fibers from a rotating drum (Fig. 10). This technique significantly increases productivity by eliminating the limitations imposed by electrostatic charge accumulation. The system can process both polymer solutions and melts, broadening the range of compatible materials. The core mechanism involves a high-speed rotating nozzle, which, when heated, melts the polymer and extrudes fibers under centrifugal force. The stretching force further refines fiber diameter and morphology, with the nanofibers subsequently collected by a capture electrode. While forcespinning enables high-throughput nanofiber production, challenges remain in controlling fiber diameter and uniformity, particularly for applications requiring precise nanoscale dimensions.

## Comparison and future considerations

Nanofiber production techniques, as disscussed, vary significantly in their scalability, fiber control, and application suitability. While methods such as melt spinning and force-spinning prioritize high production rates and solvent-free processes, electrostatic and air-jet electrospinning offer better control over fiber morphology and functionalization. Each method has distinct advantages, with melt spinning and force-spinning excelling in scalability but lacking fine control over fiber structure. In contrast, electrostatic and air-jet electrospinning allow for more precise tailoring of nanofiber properties, making them ideal for specialized applications like biomedical and filtration.

The proposed electrospinning system stands out as a solution to bridge the gap between high scalability and precise fiber control. It offers a customizable platform that can be adapted for various polymer solutions and application needs, making it versatile for different industries, particularly medical, textile, and filtration fields. However, competing with industrial-scale systems like those developed by SPUR a.s. and FibeRio Technology Corporation requires ongoing improvements in production speed, fiber consistency, and material adaptability.

The proposed electrospinning system offers several innovations that address key challenges in nanofiber production. One of the standout features is the novel electrospinning device designed for large-scale

production, which combines the benefits of dynamic mixing and a receding spinner motion. This unique design ensures consistent solution mixing, prevents polymer degradation, and improves fiber uniformity during the electrospinning process. Additionally, the rectangular spinner design with horizontal, rectilinear motion enhances the uniform coating of the polymer solution, reducing variability in fiber morphology. The inclusion of six spinning heads allows for simultaneous production of nanofibers, significantly increasing throughput compared to traditional single-spinner systems. This design is ideal for industrial applications, particularly in sectors like medical and filtration, where high-volume production is necessary without compromising fiber quality. Furthermore, the system's ability to cover a large substrate width of 1600 mm addresses the long-standing challenge of scaling up electrospinning from laboratory-scale to industrial-scale operations, making it a competitive solution for commercial use.

Despite its promising capabilities, the proposed electrospinning system faces challenges, particularly in terms of setup and maintenance costs. The integration of multiple spinners, mixing systems, and precision control mechanisms demands significant investment in equipment and operational expertise. The reliability of the spinner's motion and solution delivery over extended production cycles also needs thorough testing to ensure consistent performance in industrial settings. Furthermore, while the current system demonstrates good fiber consistency, there remains room for improvement in controlling nanofiber morphology on a finer scale, particularly concerning fiber diameter and distribution. Future research should focus on optimizing processing parameters, refining fiber alignment strategies, and exploring hybrid approaches that combine the benefits of multiple techniques. By integrating advances from multi-nozzle electrospinning, air-assisted deposition, and centrifugal processing, future systems could enhance both scalability and precision.

Additionally, optimizing the deposition rate while maintaining fiber quality will be critical for future advancements in nanofiber manufacturing. Incorporating different polymer solutions, such as biodegradable polymers or bioactive compounds, could open new possibilities for specialized applications in wound healing, drug delivery, and tissue engineering. The flexibility of the proposed system also allows for the production of multi-layered scaffolds with customized properties, such as varying porosity, hydrophilicity, and mechanical strength, offering exciting opportunities for multifunctional material design.

## CONCLUSION

In conclusion, the proposed electrospinning device demonstrates significant potential for industrial-scale nanofiber production. The novel design, with its dynamic spinner motion and multiple spinning heads, offers improved consistency, scalability, and operational efficiency compared to traditional electrospinning systems. The system's ability to mix the polymer solution in real-time and deliver uniform nanofibers positions it as a promising solution for high-throughput, large-area nanofiber fabrication.

While the device is in the prototype phase, preliminary results suggest it could have a substantial impact on the future of nanofiber manufacturing, particularly in sectors requiring high-quality, scalable materials. Continued development and optimization of the system, including cost analysis, long-term testing, and further exploration of customization options, will be essential to fully realize its industrial potential.

## REFERENCES


1. Jirsák O., Sanetrník F., Mareš L.: Lineární vlákenný útvar obsahující nanovlákna a způsob a zařízení pro jeho výrobu [online]. Patent, 305039. 25. February 2015. https://isdv.upv.gov.cz/doc/FullFiles/Patents/FullDocuments/305/305039.pdf
2. Petras D., Maly M., Pozner J, et al.: Rotary Spinning Electrode [online]. Patent, WO 2008/028428 A1. 13. March 2008. https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2008028428
3. Petras D, Mareš L, Čmelík J, et al.: Zařízení pro výrobu nanovláken elektrostatickým zvlákňováním polymerních roztoků [online]. 1. June 2006. https://isdv.upv.gov.cz/doc/FullFiles/Applications/2006/PPVCZ2006_0359A3.pdf
4. Cooley J.F.: Apparatus for Electrically Dispersing Fluids [online]. No. 692,631. 4. February 1902. https://patentimages.storage.googleapis.com/9a/27/8c/f48a4f5949a847/US692631.pdf
5. Růžičková J. Elektrostatické zvlákňování nanovláken. Liberec: Technická univerzita v Liberci, 2006. ISBN 80-7372-066-3.
6. Jirsák O., Kalinová K.: Netkané textilie. Liberec: Technická univerzita v Liberci, 2003. ISBN 80-7083-746-2.
7. Taylor S.G.: Disintegration of Water Drops in an Electric Field. In: Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. 1964, pp. 383–397.
8. Jirsak O., Sanetrnik F., Lukas D., et al.: Method of nanofibres production from a polymer solution using electrostatic spinning and a device for carrying out the method [online]. US 7,585,437 B2. 8. September 2009. https://patents.google.com/patent/US7585437B2/en
9. He J.H., Wu Y., Zuo W.W.: Critical length of straight jet in electrospinning. Polymer, 46(26), 2005, pp. 12637–12640. http://doi.org/10.1016/j.polymer.2005.10.130
10. He J.H., Xu L., Wu Y., et al.: Mathematical models for continuous electrospun nanofibers and electrospun nanoporous microspheres. Polymer International, 56(11), 2007, pp. 1323–1329. http://doi.org/10.1002/pi.2370
11. Reneker D.H., Yarin A.L., Zussman, E., et al. Electrospinning of Nanofibers from Polymer Solutions and Melts. Advances in Applied Mechanics, 41, 2007, pp 345-346. http://doi.org/10.1016/s0065-2156(07)41002-x
12. Mikeš P., Lukáš D. Fyzikální principy tvorby nanovláken I [online]. 2015, ISBN 978-80-7494-249-5. https://dspace.tul.cz/handle/15240/172699
13. Filatov Y., Budyka A., Kirichenko V.: Electrospinning of Micro- and Nanofibers: Fundamentals in Separation and Filtration Processes, New York : Begell House, 2007. ISBN 978-1-56700-241-6.

14. Almetwally A., El-Sakhawa A.A.M, Elshakankery M.H., et Technology of Nano-Fibers: Production Techniques and Properties - Critical Review, 2017.
15. Wei L., Sun R., Liu Ch., et al.: Mass production of nanofibers from needleless electrospinning by a novel annular spinneret. Materials & Design, 179, 2019, 107885. http://doi.org/10.1016/j.matdes.2019.107885
16. Vaz, B.S., Costa J.A.V., De Morais M.G. Production of polymeric nanofibers with different conditions of the electrospinning process. Matéria, 22(2), 2017. http://doi.org/10.1590/s1517-707620170002.0180
17. Kim Y.M, Sung Y.B., Jang R.S., et al.: A manufacturing device and the method of preparing for the nanofibers via electro-blown spinning process. Patent, WO 03/080905 A1. 2. October 2003. https://patents.google.com/patent/WO2003080905A1/en?oq=WO+03080905
18. Bryner M.A., Armantrout J.E., Scott B.: Electroblowing web formation process. Patent, US 2006/0138710 A1. 29. June 2006.
19. Knížek R., Karhánková D., Bajzík V., et al.: Zařízení pro výrobu nanovláken elektrostatickým zvlákňováním roztoku nebo taveniny polymeru [online]. Utility Model, 27438. https://isdv.upv.gov.cz/doc/FullFiles/UtilityModels/FullDocuments/FDUM0027/uv027438.pdf
20. Knížek O.: New design solution for spinning process equipment. Liberec, 2023, Bachelor Thesis, Technical University of Liberec.