# CONTINUOUS NANOFIBROUS YARN PREPARATION BY ELECTROSPINNING FOR SUSTAINABLE TEXTILE MATERIAL

**Faisal S. Rahaman[1,5], Mubarak A. Khan[*1,2], M. S. Jahan[1,3], Fairuz L. Oishi[4], and Abu S. Monshi[5]**

[1] *Research Lab, Echotex Ltd., Gazipur, Bangladesh, e-mail: faisal.shagor@gmail.com*
[2] *Bangladesh Jute Mills Corporation, Dhaka – 1000, Bangladesh, e-mail: makhan.inst@gmail.com*
[3] *Department of Material and Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, e-mail: sarwarjahan235@gmail.com*
[4] *Govt. Edward College, National University of Bangladesh, Pabna, Bangladesh, e-mail: f.oishorjo@gmail.com*
[5] *Pabna Textile Engineering Collage, Bangladesh University of Textiles, Pabna, Bangladesh, e-mail: sayedmonshi@gmail.com*

***Corresponding Author**

## ABSTRACT

Electrospinning is a versatile, viable, and efficient technique for the preparation of nano-scale fibers using organic and inorganic polymers. It creates a random arrangement of nanofiber onto the collector and creates a nonwoven structure that contains a significant number of isotropic pores that remain evenly distributed throughout the fibers. Its versatile utility spans a wide array of applications, including textiles, filtration of air and water, tissue engineering, scaffolding, composites, biomedical engineering, and others. This study concentrates on the production of continuous nanofibrous yarn via electrospinning focusing on sustainable textile materials. Among several possible approaches, water-based collector system was adopted. The used polymeric solution was 10% cellulose acetate in a polar solvent. The electrospinning parameters were – applied high voltage: 15kv, tip to collector distance: 10cm, solution inject rate: 1ml/h, internal diameter of needle: 0.50mm, collector rotation speed: 50rpm. After that, the morphologies of Yarn and Fiber were observed and evaluated. FTIR showed the peaks at 1742cm$^{-1}$, 1434cm$^{-1}$, 1369cm$^{-1}$, 1230cm$^{-1}$, and 1035cm$^{-1}$ confirmed the cellulose acetate material. It is imperative to subject the nanofibrous yarns to comprehensive testing, including evaluations of tensile strength, breaking elongation, yarn count, and other relevant parameters for the implementation in textile sector. Collectively, these characterizations will underscore the suitability of electrospun nanofibrous continuous yarn as a sustainable textile material.

***Keywords:*** *Electrospinning, Nanofiber, Continuous Yarn, Sustainable Textiles*

## 1. INTRODUCTION

Electrospinning is a versatile, viable and efficient technique for preparing ultrathin, micro, and nano scale fibers of organic and inorganic polymers. Electrospinning creates a random arrangement of nanofiber onto the collector and creates a nonwoven structure which contains a significant number of isotropic pores that remains evenly distributed throughout the fibers (Xue et al., 2019; Zhang, Wang, et al., 2021). It has a wide range of smart application like filtration of air and water, tissue engineering, adsorption and catalytic material, scaffold, composite, biomedical engineering and so on (Chen et al., 2020; K. S. Han et al., 2019; Huang et al., 2003; Lee et al., 2020; Sun et al., 2021).

Cellulose is the most abundant biomacromolecule polymer, and its derivatives are widely involved in the treatment of contaminated water in the form of electro-spun nanofibers, not just because of the nanostructures that are inherent to them, but also because of the active functional groups and, as a result, the superior surface chemistry that they possess. It is not only due to their intrinsic nanostructures but also owing to their active functional groups and subsequently good surface chemistry. Cellulose Acetate easily dissolves in common solvents and a desirable carrier for loading other polymers and functional fillers with desired properties. It is also thought to be nontoxic, non-irritating, and biodegradable (Zhang, Zhang, et al., 2021).

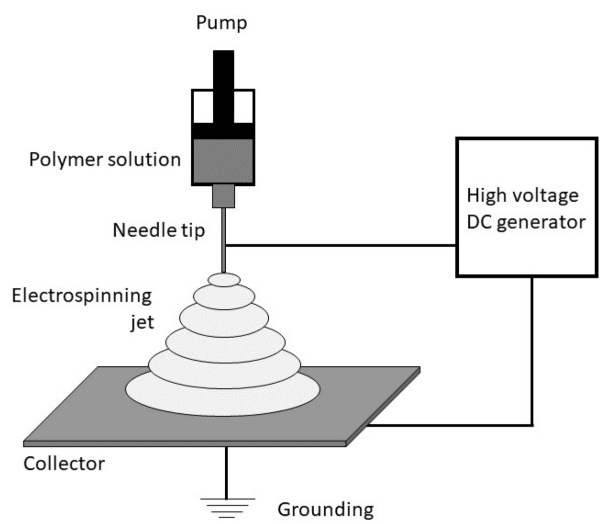


Figure 1: Basic electrospinning principal using single polymeric solution

The electrospinning principle is pretty simple: A solution of a polymer flows from the tip of a capillary, where a droplet forms as a result of the solution's surface tension. A suitable strong electric charge is given to the solution, which allows the electrostatic interactions between polymer and solvent molecules to overcome the surface tension, resulting in the expulsion of polymer from the capillary towards a grounded collector. In the region between the tip of the capillary and the collector, the jet becomes unstable, and rapid turbulence ensues. This results in the evaporation of the solvent, leaving behind a polymer fiber that undergoes stretching and thinning as a result of the whipping, and finally collects as a randomly oriented web of micro or nanofibers on the grounded collector (Smit et al., 2005).

The textile industry is undergoing a paradigm shift towards sustainability, seeking innovative approaches to reduce environmental impact. One such groundbreaking technique is the preparation of continuous nanofibrous yarns through electrospinning. Electrospinning, a process that transforms polymeric solutions into ultrafine fibers at the nanoscale, holds immense potential for creating sustainable textile materials. This essay explores the significance of electrospun nanofibrous yarns in the context of sustainable textiles, highlighting their unique properties and contributions to eco-friendly manufacturing practices (Harsanto et al., 2023; Thakker & Sun, 2023).

Electrospinning technology facilitates the development of nanofibrous yarns with remarkable characteristics that set them apart in the realm of sustainable textiles. These yarns, comprised of nanoscale fibers, possess an increased surface area, flexibility, and enhanced mechanical strength. The ability to precisely control the diameter and composition of these fibers enables the customization of yarns for specific applications, addressing performance and sustainability requirements simultaneously. The environmental advantages of electrospun nanofibrous yarns are manifold. By employing this technique, manufacturers can significantly reduce material consumption while maintaining or even enhancing product performance. The high surface area-to-volume ratio of nanofibers allows for efficient resource utilization, making them ideal for applications where lightweight and breathable textiles are essential. Additionally, the electrospinning process typically employs lower quantities of materials compared to traditional methods, contributing to a reduction in waste generation. Moreover, the resulting nanofibrous yarns exhibit superior properties that align with the principles of sustainable textile design. Enhanced breathability and moisture management, key attributes of these yarns, contribute to wearer comfort and reduce the need for energy-intensive treatments to achieve similar effects. The durability and strength of nanofibrous textiles can extend the lifespan of garments, diminishing the frequency of replacements and, consequently, the environmental burden associated with textile disposal. The versatility of electrospinning technology allows for the utilization of various biodegradable and environmentally friendly polymers in the creation of nanofibrous yarns. As the textile industry explores alternatives to conventional materials, these sustainable polymers offer a pathway to reducing reliance on non-renewable resources and mitigating the environmental impact of textile production (Castel, 2023; Mazari et al., 2020; Nayak & Padhye, 2017; Ravandi et al., 2015).

Sustainability is defined as development that meets the needs of the present without sacrificing the potential for future generations to meet their needs and the goal of sustainability is to meet present needs without endangering the capacity of future generations to meet their own. The three pillars of sustainability—profit, planet, and people—are economically, ecologically, and socially driven. Businesses are becoming more and more transparent about their commitment to sustainability by promoting programs like waste reduction, investing in renewable energy, and supporting organizations that strive for a more sustainable society. The contemporary real estate industry promotes a green environment through sustainability. Enhancing fabric materials' performance and adding new features would be very helpful for occupations like emergency response services and the armed forces (Chowdhury et al., 2021; Jalil et al., 2011; Radhakrishnan, 2014; Sinha et al., 2018).

## 2. METHODOLOGY

### 2.1 Materials

Cellulose Acetate (CA) containing acetyl group 29-45% of Loba Chemie, India was purchased from local market and Dimethylformamide (DMF) was bought from Merck Millipore, Germany. All chemicals were reagent grade and further purification was not required.

### 2.2 Polymer solution preparation

10% of CA as a polymer solution was used for all the experiment. The solvent for the Cellulose Acetate solution (CA) was Dimethylformamide (DMF). They were taken in a beaker and kept for mixing with gentle stirring with a magnetic bar at room temperature and atmospheric pressure for 12h to disperse properly in the solution.

### 2.3 Electrospinning setup

The electrospinning/spraying system used for the preparation of the CA electro-spun nanofiber yarn, was the es-ROBOT® ESR200RD bought from NanoNC, South Korea. The es-High Voltage Power Supply system was combined with the machine to generate high voltage as requiring for the construction of sample. The CHkawai DH-902B was used as a humidity control system during the electrospinning and HSW-HENKE-JECT® syringe pump was used for the solution pumping.

To run the electrospinning process, polymer solution was put into a syringe equipped with a blunt-end, 21-gauge metal needle that was positioned in a syringe pump. By applying a high voltage between 14kV and 15 kV to the needle tip, nanofibers were electro-spun to produce yarn. The Tip to Collector Distance (TCD) was 10 cm and was kept constant in all the experiments. The syringe pump delivered the polymer solutions at a controlled flow rate, ranging from 0.50ml/h to 0.80mL/h and total volume of the injected solution was 10ml. All the experiments were performed at least twice. The resulting fibers were collected on a coagulation bath to produce nanofibrous yarn.

### 2.4 Yarn preparation

The resulting fibers were collected on a coagulation bath to produce nanofibrous yarn. A manually set take-up roller was used to run at a required speed equivalent to a linear take-up speed. The initial non-woven web of fibers that formed on the surface of the water was then drawn, with the aid of a glass rod, across the surface of the water and scooped off into air. The aligned and entangled fibrous yarn was then linked by carefully drawing it by hand to the manually rotating take-up roller and winding it around the roller once. After that, the coiled yarn is gathered and unwound before going through a drying unit to finish drying.

### 2.5 Characterization

The morphology of the nanofibrous yarns was studied with a Fourier Transform Infrared Radiation (FTIR) spectroscopy, Regular Microscope, and a Scanning Electron Microscope (SEM) to study the fiber entanglement in the yarn, longitudinal view, nanofiber size and others.

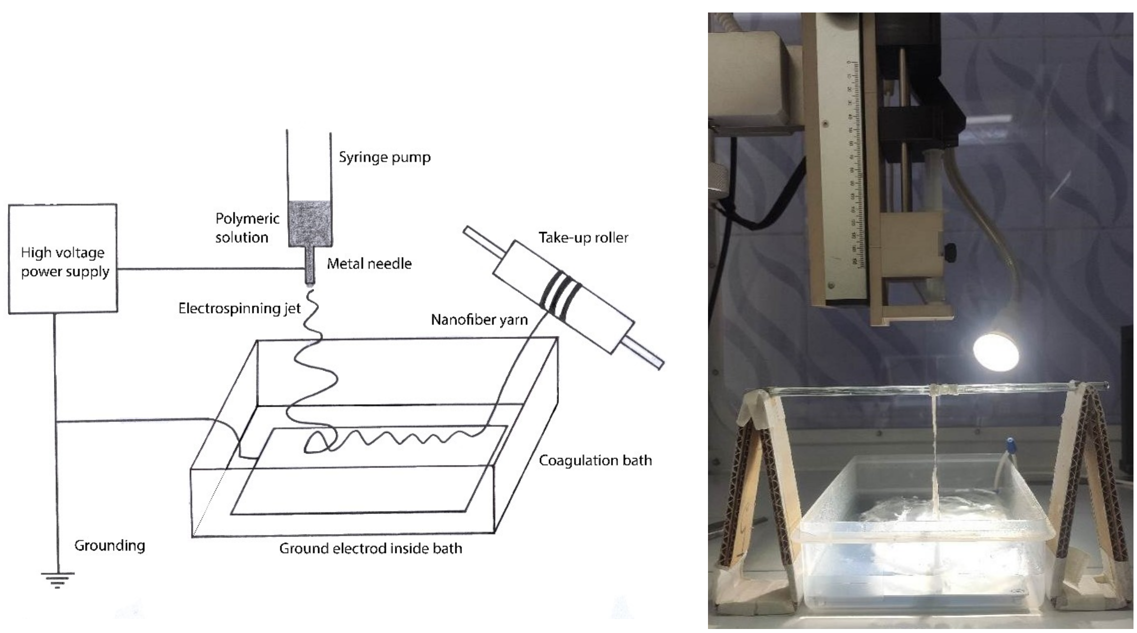


Figure 2: Nanofibrous yarn making principal through Electrospinning

## 3. RESULT AND DISCUSSION

The alterations in the chemical structure of cellulose acetate (CA) nanofibers were meticulously examined through Fourier Transform Infrared (FTIR) spectroscopy. Notably, after about a 370-minute electrospinning process, distinct changes were observed in the FTIR spectrum, showcasing characteristic absorption peaks of CA. CA exhibits the C=O stretching absorption within the range 1735 $cm^{-1}$ – 1750 $cm^{-1}$ and the peak has been found strongly at 1742 $cm^{-1}$ indicates an ester group, another two strong peak has been raised at 1230 $cm^{-1}$ and 1040 $cm^{-1}$ indicates $CH_3$-C=O and C–O–C stretching indicates an acetyl ester and a carbonyl group respectively, which are the characteristics of cellulose acetate. These peaks are indicative of the presence of CA, the primary constituent of the electrospun nanofibers (Djuned et al., 2014; S. O. Han et al., 2008; He, 2017).

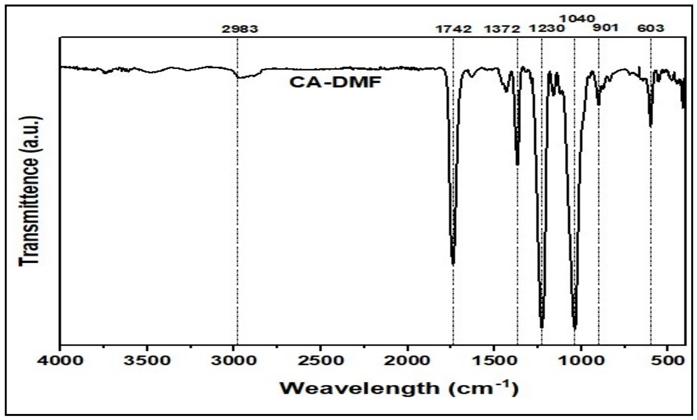


Figure 3: Fourier Transform Infrared Radiation study of CA-DMF nanofiber yarn

In Figure 4, the microscopic view (A) provides a regular perspective, while (B) presents Scanning Electron Microscopic (SEM) micrographs of the CA-based electrospun nanofiber yarn, which was fabricated from a 10 wt.% CA solution in DMF. Importantly, the SEM images reveal the preservation of the nonwoven mat structure of the CA nanofibers during the electrospinning process on the coagulation bath. Notably, there is no discernible degradation, and the integrity of the CA nanofiber structure is well-maintained.

This visual confirmation of the nonwoven mat structure's retention underscores the robustness of the electrospinning process, and the SEM micrographs provide a detailed insight into the morphology of the resulting nanofibrous yarn. The absence of observable degradation further supports the viability and stability of the electrospinning technique, emphasizing its potential for the production of cellulose acetate nanofiber yarns with maintained structural integrity and chemical composition.

There are a number of parameters that can influence electrospinning results. The concentration of the polymer solution significantly influences electrospinning outcomes. Higher concentrations generally result in thicker fibers due to increased material content in the ejected jet, but extremely high concentrations may lead to increased solution viscosity, affecting the jet's stability. The choice of solvent or solvent blend is also crucial. Solvents affect the polymer's solubility, solution viscosity, and drying rate. Fast-evaporating solvents can lead to rapid jet solidification, impacting fiber morphology. On the other hand, slow-evaporating solvents may allow for greater fiber stretching. Besides, the voltage applied during electrospinning determines the electrostatic forces acting on the polymer jet. Higher voltages create stronger forces, leading to thinner fibers but, excessively high voltages can also cause instabilities in the jet, affecting fiber uniformity. The rate at which the polymer solution is extruded, known as the flow rate, influences fiber diameter. Higher flow rates generally result in thicker fibers due to increased material deposition. Balancing the flow rate with other parameters is essential to achieve desired fiber characteristics. Another thing is the distance between the spinneret and collector (TCD=Tip to collector distance) affects the time available for solvent evaporation and fiber stretching. Short distances may not allow sufficient stretching, while long distances can result in a loss of control over the jet, affecting fiber uniformity. Besides, collector type (solid or rotating) and its speed influence fiber alignment and distribution also. Rotating collectors can lead to aligned fibers, while variations in collector speed impact fiber deposition patterns. Proper control over collector parameters is vital for achieving specific fiber orientations. There is also an important factor that is the environmental conditions where the experiments take place. It plays vital a role in the electrospinning process. Higher temperatures and humidity levels can influence the drying rate of the polymer solution. Humidity, in particular, can affect the solvent evaporation rate, potentially altering fiber morphology. Inherent properties of the polymer, such as molecular weight and chain entanglement, affect the solution's viscosity and electrospinnability. Understanding these properties helps in selecting appropriate process parameters. One more thing, introducing additives or crosslinking agents can modify the properties of the resulting fibers. Additives may influence the solution's viscosity, while crosslinking agents can enhance the mechanical and chemical stability of the fibers. And finally, the duration of electrospinning, or process time, impacts the thickness of the fiber mat. Longer spinning times can lead to denser mats, affecting properties like porosity and surface area (Bae et al., 2020; Haider et al., 2018; Kailasa et al., 2021; Nayak & Padhye, 2017; Ramakrishna et al., 2007; Tan et al., 2005).

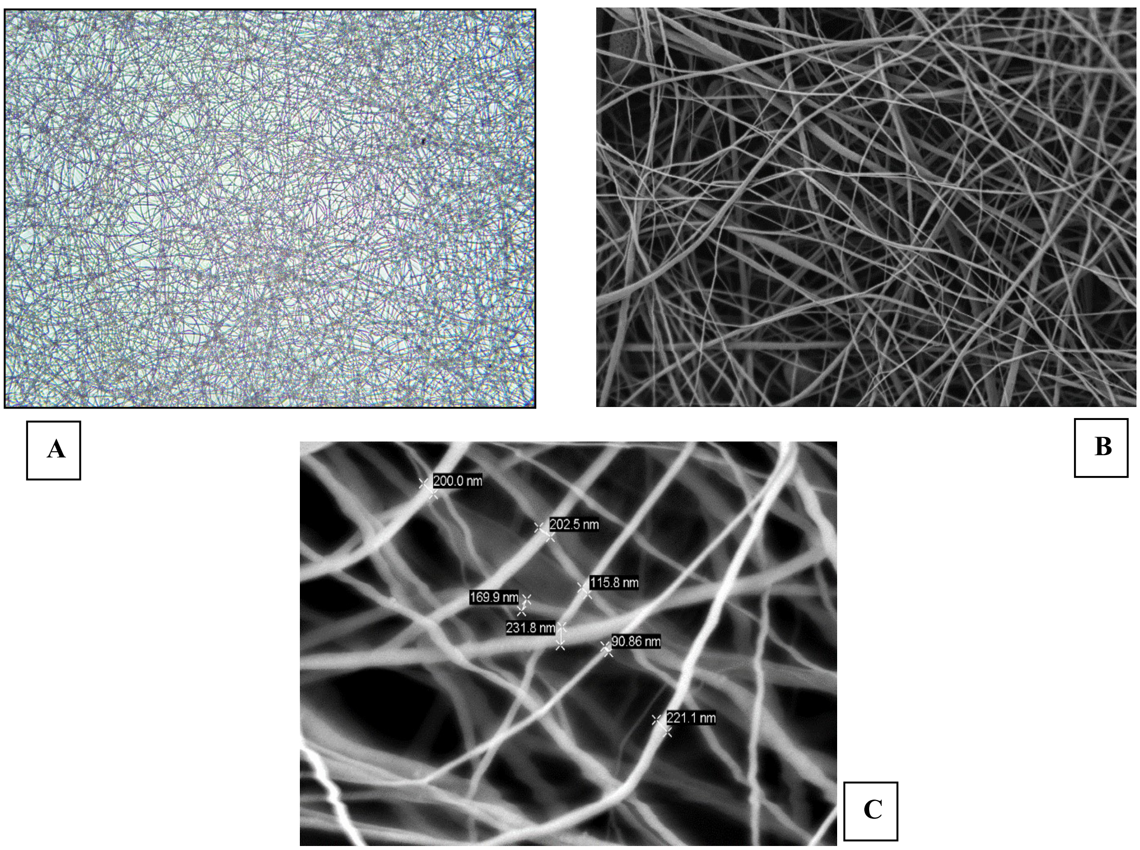


Figure 4: (A) Microscopic view, (B) SEM Image, (C) Irregular nanofiber size of electrospun nanofibrous yarn

While electrospinning happens onto a solid collector, there is a consistent observation of an increase in fiber diameters with a rise in solution concentration. This phenomenon is accompanied by the presence of bead-like structures and variations in fiber thickness, characteristics that tend to diminish in size or disappear entirely as the solution concentration is elevated. These trends are not exclusive to solid collectors; similar observations have been noted when electrospinning onto a water bath collector.

Comparative analysis of yarns produced from solutions with different concentrations reveals distinct outcomes. Yarns derived from higher concentrated solutions exhibit larger fibers with an average diameter of 1 nm and occasional bead formations. In contrast, yarns from lower concentrated solutions result in an average fiber diameter of 294 nm with pronounced bead formations (Deitzel et al., 2001; Fong et al., 1999; Ryu et al., 2020). In the specific experiment discussed, a 10% polymeric solution was utilized, yielding a fiber diameter range of 90 nm to 232 nm and an average diameter of 176 nm, as depicted in Figure 4.

The process of yarn formation can be delineated into three phases. The initial two phases unfold in two dimensions, while the third phase transitions into three dimensions. In the first phase, a flat web of fibers materializes on the water bath surface, featuring randomly looped fibers. The second phase involves the elongation of the fiber web as it is drawn over or through the water, leading to alignment among the fibers. The third phase is characterized by drawing the web off the water into the air, wherein the surface tension of the residual water on the web induces the fibers to coalesce into a three-dimensional, rounded yarn structure.

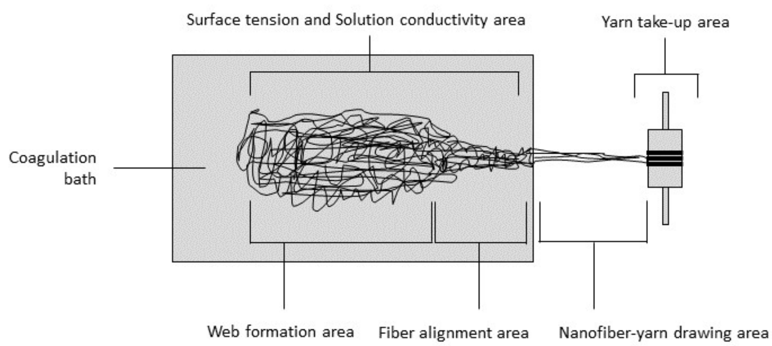


Figure 5: Fiber alignment and yarn take-up principals

Further investigations have unveiled the influential role of water conductivity and surface tension in this process. Notably, the molecular weight of the polymeric solution influences the sinking of fibers in the distilled water bath. This sinking effect contributes to heightened drag on the drawn yarn, revealing the intricate interplay of solution properties and collector dynamics in shaping the final structure of electrospun nanofibrous yarns.

## 4. CONCLUSION

In this research, we have outlined a novel approach for creating continuous yarns utilizing electrospun nanofibers of cellulose acetate so that it can be implemented in knitting and weaving sections in textile sectors for sustainable fashion in the near future.

The resulting yarns demonstrate a high degree of alignment among the fibers and exhibit characteristic features associated with electrospinning, such as a dependence on fiber diameter relative to concentration and the presence of thick and thin portions. What sets this method apart is its simplicity and the noteworthy production rate of yarns, rendering it particularly advantageous for laboratory-scale manufacturing of electrospun nanofiber yarns. Our method's user-friendly nature holds promise for widespread adoption and experimentation in research settings. Additionally, given its efficiency in yarn production, there is potential for further exploration of this method on a larger scale, possibly paving the way for commercial applications. To transition from laboratory experimentation to commercial viability, it is imperative to subject the nanofibrous yarns to comprehensive testing, including evaluations of tensile strength, yarn count, and other relevant parameters. These tests will not only validate the practicality and durability of the electrospun nanofiber yarns but also provide essential data for optimizing the manufacturing process to meet commercial standards.

Looking ahead, the envisioned future of this technology involves refining and scaling up the production process, with a keen focus on addressing the intricacies of commercial manufacturing. This may involve streamlining the production pipeline, ensuring consistent quality, and assessing the economic feasibility of large-scale production. Ultimately, the goal is to bridge the gap between innovative laboratory techniques and real-world applications, facilitating the potential commercialization of nanofibrous yarns for a diverse range of industries.

This continuous nanofibrous yarn production through electrospinning stands at the forefront of sustainable textile materials. This innovative approach leverages nanotechnology to redefine the properties of textiles, fostering eco-friendly practices in the manufacturing sector. The unique attributes of electrospun nanofibrous yarns, coupled with their potential for reducing material usage and enhancing product performance, position them as a promising solution for the evolving landscape of sustainable textiles. As the world gravitates towards a more environmentally conscious future, the integration of electrospun nanofibrous yarns into textile production heralds a new era of responsible and sustainable fashion.

## ACKNOWLEDGEMENT

The authors are very thankful to Echotex Limited, Gazipur, Bangladesh for providing all raw materials, chemicals and machineries required for this research.

## REFERENCES

Bae, J., Kim, H., Park, S., Kim, K. S., & Choi, H. (2020). Parametrization study of electrospun nanofiber including licl using response surface methodology (Rsm) for water treatment application. *Applied Sciences (Switzerland)*, *10*(20), 1–16. https://doi.org/10.3390/app10207295

Castel, L. (2023). *Green Electrospinning : Making Electrospinning Environmentally Friendly*. 1–10.

Chen, W., Ma, H., & Xing, B. (2020). Electrospinning of multifunctional cellulose acetate membrane and its adsorption properties for ionic dyes. *International Journal of Biological Macromolecules*, *158*, 1342–1351. https://doi.org/10.1016/j.ijbiomac.2020.04.249

Chowdhury, N., Faysal, G. M., Al, A., Shikder, R., & Moula, A. (2021). A study on sustainable fashion supply chain of zara. *6th Int. Conf. Eng. Res. Innov. Educ., Sylhet, Bangladesh*, *October 2022*, 1.

Deitzel, J. M., Kleinmeyer, J., Harris, D., & Tan*, N. C. B. (2001). The effect of processing variables on the morphology of electrospun nanofibers and textiles. *Polymer*, *42*(2), 261–272.

Djuned, F. M., Asad, M., Ibrahim, M. N. M., & Daud, W. R. W. (2014). Synthesis and characterization of cellulose acetate from TCF oil palm empty fruit bunch pulp. *BioResources*, *9*(3), 4710–4721. https://doi.org/10.15376/biores.9.3.4710-4721

Fong, H., Chun, I., & Reneker, D. H. (1999). Beaded nanofibers formed during electrospinning. *Polymer*, *40*(5), 881–888. https://doi.org/10.1080/21691401.2016.1185726

Haider, A., Haider, S., & Kang, I. K. (2018). A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and biotechnology. *Arabian Journal of Chemistry*, *11*(8), 1165–1188. https://doi.org/10.1016/J.ARABJC.2015.11.015

Han, K. S., Lee, S., Kim, M., Park, P., Lee, M. H., & Nah, J. (2019). Electrically Activated Ultrathin PVDF-TrFE Air Filter for High-Efficiency PM1.0 Filtration. *Advanced Functional Materials*,

*29*(37), 1–7. https://doi.org/10.1002/adfm.201903633
Han, S. O., Youk, J. H., Min, K. D., Kang, Y. O., & Park, W. H. (2008). Electrospinning of cellulose acetate nanofibers using a mixed solvent of acetic acid/water: Effects of solvent composition on the fiber diameter. *Materials Letters*, *62*(4–5), 759–762. https://doi.org/10.1016/j.matlet.2007.06.059
Harsanto, B., Primiana, I., Sarasi, V., & Satyakti, Y. (2023). Sustainability Innovation in the Textile Industry: A Systematic Review. *Sustainability (Switzerland)*, *15*(2). https://doi.org/10.3390/su15021549
He, X. (2017). Fabrication of defect-free cellulose acetate hollow fibers by optimization of spinning parameters. *Membranes*, *7*(2). https://doi.org/10.3390/membranes7020027
Huang, Z. M., Zhang, Y. Z., Kotaki, M., & Ramakrishna, S. (2003). A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology*, *63*(15), 2223–2253. https://doi.org/10.1016/S0266-3538(03)00178-7
Jalil, M. A., Rokonuzzaman, M., Razzaque, A., & Afroz, N. (2011). Effect of Delivery Speed of Winding Machine on Yarn Hairness. *J.Innov.Dev.Strategy*, *I*(April), 6–8.
Kailasa, S., Reddy, M. S. B., Maurya, M. R., Rani, B. G., Rao, K. V., & Sadasivuni, K. K. (2021). Electrospun Nanofibers: Materials, Synthesis Parameters, and Their Role in Sensing Applications. *Macromolecular Materials and Engineering*, *306*(11), 1–36. https://doi.org/10.1002/mame.202100410
Lee, S., Franklin, S., Hassani, F. A., Yokota, T., Nayeem, M. O. G., Wang, Y., Leib, R., Cheng, G., Franklin, D. W., & Someya, T. (2020). Nanomesh pressure sensor for monitoring finger manipulation without sensory interference. *Science*, *370*(6519), 966–970. https://doi.org/10.1126/SCIENCE.ABC9735/SUPPL_FILE/ABC9735_LEE_SM.PDF
Mazari, S. A., Mubarak, N. M., Jatoi, A. S., Abro, R., Shah, A., Shah, A. K., Sabzoi, N., Baloch, H., Kumar, V., & Lghari, Z. (2020). Environmental impact of using nanomaterials in textiles. In *Nanosensors and Nanodevices for Smart Multifunctional Textiles*. INC. https://doi.org/10.1016/B978-0-12-820777-2.00018-2
Nayak, R., & Padhye, R. (2017). Nano Fibres by Electro spinning: Properties and Applications. *Journal of Textile Engineering & Fashion Technology*, *2*(5), 486–497. https://doi.org/10.15406/jteft.2017.02.00074
Radhakrishnan, S. (2014). *Roadmap to Sustainable Textiles and Clothing*. 41–62. https://doi.org/10.1007/978-981-287-065-0
Ramakrishna, S., Fujihara, K., Teo, W.-E., Lim, T.-C., & Ma, Z. (2007). An Introduction to Electrospinning and nanofibers. In *World Scientific Publishing*. http://hdl.handle.net/2268/11512
Ravandi, S. A. H., Tork, R. B., Dabirian, F., Gharehaghaji, A. A., & Sajjadi, A. (2015). Characteristics of Yarn and Fabric Made out of Nanofibers. *Materials Sciences and Applications*, *06*(01), 103–110. https://doi.org/10.4236/msa.2015.61013
Ryu, H. Il, Koo, M. S., Kim, S., Kim, S., Park, Y. A., & Park, S. M. (2020). Uniform-thickness electrospun nanofiber mat production system based on real-time thickness measurement. In *Scientific Reports* (Vol. 10, Issue 1). https://doi.org/10.1038/s41598-020-77985-0
Sinha, M., Das, B., Prasad, N., Kishore, B., & Kumar, K. (2018). Exploration of nanofibrous coated webs for chemical and biological protection. *Zastita Materijala*, *59*(2), 189–198. https://doi.org/10.5937/zasmat1802189k
Smit, E., Buttner, U., & Sanderson, R. D. (2005). Continuous yarns from electrospun fibers. *Polymer*, *46*(8), 2419–2423. https://doi.org/10.1016/j.polymer.2005.02.002
Sun, X., Bai, L., Li, J., Huang, L., Sun, H., & Gao, X. (2021). Robust preparation of flexibly super-hydrophobic carbon fiber membrane by electrospinning for efficient oil-water separation in harsh environments. *Carbon*, *182*, 11–22. https://doi.org/10.1016/j.carbon.2021.05.047
Tan, S. H., Inai, R., Kotaki, M., & Ramakrishna, S. (2005). Systematic parameter study for ultra-fine fiber fabrication via electrospinning process. *Polymer*, *46*(16), 6128–6134. https://doi.org/10.1016/j.polymer.2005.05.068
Thakker, A. M., & Sun, D. (2023). Sustainable Development Goals for Textiles and Fashion. *Environmental Science and Pollution Research*, *30*(46), 101989–102009. https://doi.org/10.1007/s11356-023-29453-1
Xue, J., Wu, T., Dai, Y., & Xia, Y. (2019). Electrospinning and electrospun nanofibers: Methods,

materials, and applications [Review-article]. *Chemical Reviews*, *119*(8), 5298–5415. https://doi.org/10.1021/acs.chemrev.8b00593

Zhang, Y., Wang, F., & Wang, Y. (2021). Recent developments of electrospun nanofibrous materials as novel adsorbents for water treatment. *Materials Today Communications*, *27*(November 2020), 102272. https://doi.org/10.1016/j.mtcomm.2021.102272

Zhang, Y., Zhang, C., & Wang, Y. (2021). Recent progress in cellulose-based electrospun nanofibers as multifunctional materials. *Nanoscale Advances*, *3*(21), 6040–6047. https://doi.org/10.1039/d1na00508a