

## Cellulose Electrospun Nanofibers: Bridging Sustainability and Electronics

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**Abstract:** The pursuit of sustainable and high-performance materials has spotlighted cellulose-based electrospun nanofibers for electronic applications. Derived from the abundant biopolymer cellulose, these nanofibers combine biodegradability, renewability, and mechanical strength with the benefits of electrospinning, such as high surface area and tunable properties. This review examines the synthesis, characterization, and functionalization of cellulose nanofibers, emphasizing their role in flexible electronics, energy storage, sensors, and conductive composites. Despite challenges in scalability and performance optimization, advancements show improved conductivity and mechanical properties. Future directions highlight the transformative potential of these eco-friendly materials, aiming to foster further research and development towards a sustainable and efficient electronic industry. The main aim in the future direction is to advance research and development of cellulose-based electrospun nanofibers to create sustainable and high-performance materials for electronic applications. This involves overcoming challenges in scalability and optimizing performance to enhance conductivity and mechanical properties, ultimately contributing to a more sustainable and efficient electronic industry. The focus is on harnessing the eco-friendly nature of these materials to drive innovation in flexible electronics, energy storage, sensors, and conductive composites, paving the way for greener technological solutions.

**Keywords:** cellulose nanofibers; electrospinning; sustainable electronics; functionalization; energy storage

### INTRODUCTION

Electronics materials have undergone significant advancements in recent years, driven by the need for innovative, sustainable, and efficient solutions. Among the various materials explored, cellulose-based electrospun nanofibers have emerged as a promising candidate due to their unique combination of properties. Derived from natural sources, cellulose is the most abundant biopolymer on Earth, known for its biodegradability, renewability, and excellent mechanical strength [1]. When processed into electrospun nanofibers, cellulose exhibits remarkable characteristics such as high surface area, flexibility, and the potential for functionalization, making it an attractive material for a wide range of electronic applications.

The process of electrospinning provides an effective method for fabricating cellulose-based nanofibers with controlled morphology and properties. This technique offers significant advantages, including simplicity, and the ability to produce continuous fibers. The resulting nanofibers can be tailored to meet specific

requirements, such as enhanced conductivity, improved mechanical properties, and increased surface reactivity, through various pre-processing and post-processing treatments and incorporation of functional additives.

Electrospinning is a simple and effective technique for creating nanofiber membranes with large specific surface areas, carefully regulated fibre alignments, and porous surfaces. Because of these qualities, electrospun nanofibers may be used in a variety of fields, such as biomedical, energy, catalysis, sensors, and filtration [2]. The integration of cellulose-based electrospun nanofibers into electronic devices opens new possibilities for sustainable and high-performance materials. Moreover, their potential applications span a diverse array of fields, including flexible and wearable electronics, energy storage devices, sensors, and conductive composites. As researchers continue to explore and optimise the properties of these nanofibers, the intersection of material science, engineering, and electronics promises to yield innovative solutions that address the growing demand for environmentally friendly and efficient electronic materials.

In this paper the recent advancements in the development and application of cellulose-based electrospun nanofibers as electronic materials are discussed. This review covers the synthesis methods, structural characterization, and functionalization techniques used in current and possible future applications that enable these nanofibers to meet the stringent requirements of modern electronic devices. Furthermore, we will highlight the challenges and future directions in this rapidly evolving field, emphasizing the potential impact of cellulose-based nanofibers on the future of electronics.

## SYNTHESIS METHODS

Several methods are used to synthesize cellulose nanofibers. These include electrospinning of cellulose, cellulose derivatives, and nanocellulose [3].

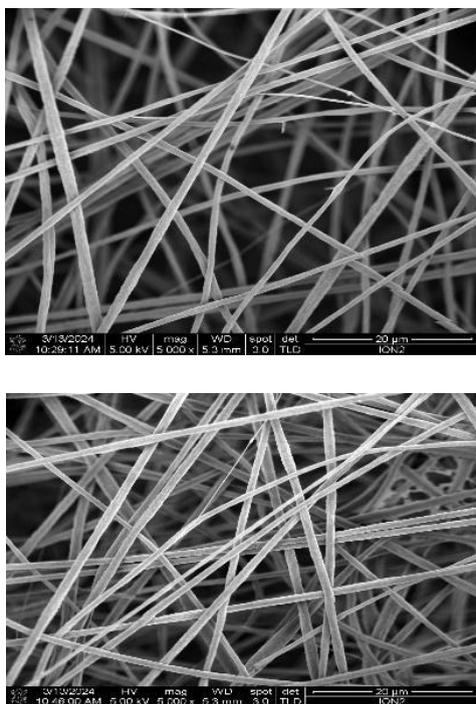
**Electrospinning of cellulose:** This process involves an electric field to draw thin fibers from a cellulose solution. It allows for the creation of continuous cellulose nanofibers with diameters typically in the nanometer range.

**Electrospinning of cellulose Derivatives:** Similar to the electrospinning of pure cellulose, this method involves using cellulose derivatives, such as cellulose acetate or carboxymethyl cellulose, as the starting material. These derivatives can be more easily dissolved in solvents, facilitating the electrospinning process.

**Electrospinning of Nanocellulose:** Nanocellulose, which includes cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), can also be electrospun to produce nanofibers. This technique often involves blending nanocellulose with other polymers to achieve the desired fiber characteristics and stability.

Electrospinning of cellulose involves dissolving pure cellulose in a suitable solvent system, such as a mixture of DMF and PAN, or an ionic liquid. The polymer-solvent system and the necessary fibre characteristics determine the optimal stirring time. The electrospinning process is affected differently by longer and shorter stirring durations [4]. The cellulose solution is then loaded into a syringe equipped with a needle, connected to a high-voltage power supply. When voltage is applied, the electrostatic force creates a jet of the solution that travels towards a grounded collector. As the jet travels, the solvent evaporates, leaving behind cellulose nanofibers. This method allows for the production of continuous fibers with diameters ranging from nanometers to micrometers, with fiber morphology controlled by adjusting

parameters like solution concentration, voltage, and needle-to-collector distance.



**Fig.1.** Shows the structure of Cellulose Acetate nanofibers

Nanofiber synthesis requires a specific electrospinning setup tailored to experimental conditions. A setup with a 25 cm gap between the needle and collecting plate, using a stainless steel No. 23 needle, is critical for optimizing fiber formation. This configuration enables proper polymer jet stretching, solidification, and solvent evaporation, producing uniform, defect-free fibers. The stainless steel needle ensures precise flow control and maintains a stable electric field, enhancing fiber consistency and quality. This setup is crucial for generating reproducible, high-quality fibers suitable for filtration, tissue engineering, and drug delivery. The solution volume was maintained at 4 mL, with a voltage range of 25–30 kV and a flow rate of 1 mL h<sup>-1</sup>. The positive electrode was connected to the high-voltage needle, and the negative electrode was attached to the stainless-steel collecting plate [5].

Dissolving cellulose in conventional solvents poses challenges due to its high viscosity, necessitating specific solvent systems. Solvent systems that promote the disentanglement or decrystallization of cellulose have been identified, facilitating its dissolution process [6]

## CELLULOSE ELECTROSPUN NANOFIBERS CHARACTERIZATION

Following electrospinning, cellulose nanofibers are characterized using various techniques to assess their physical, chemical, and thermal properties. The electrospun polymer fibers demonstrate several notable attributes, including enhanced mechanical properties such as increased tensile strength and stiffness, as well as an exceptionally high surface-area-to-volume ratio, which can be up to 103 times that of the nanofiber [1]

### Morphology and mechanical properties

Morphological and physical characterization of nanofibers is crucial for their classification and future development. In the case of cellulose electrospun nanofibers, properties such as solution homogeneity, fiber diameter, and bead presence can be assessed using scanning electron microscopy (SEM) and tensile strength can be measured with a universal tensile machine (UTM). The nanofiber webs, with an average diameter of 950 ± 50 nm, were found to be largely defect-free, with no significant bead formation, and were produced continuously under optimized electrospinning conditions. These findings provide a basis for future research [4].

The mechanical properties of two formulations, PAN (Polyacrylonitrile) and PAN with CA (Polyacrylonitrile with cellulose acetate), were evaluated and compared as shown in Table 1. PAN demonstrated a higher tensile strength at maximum load (8.39%) in contrast to PAN with CA, which exhibited a lower value (1.33%). This suggests that PAN can endure a greater force before failure. Conversely, PAN with CA showed a markedly higher

tensile strain at break (37.09%) compared to PAN (23.79%), indicating superior elasticity and the ability to elongate more before breaking. In terms of stiffness, PAN with CA exhibited a higher modulus (19.29 MPa), reflecting greater resistance to deformation under stress, whereas PAN had a lower modulus (15.04 MPa), implying greater flexibility. Furthermore, the tensile extension at maximum load for PAN (2.60 mm) was significantly higher than that of PAN with CA (0.41 mm), reinforcing the observation that PAN possesses greater flexibility. While the flexibility of PAN was noted to be higher, no specific data on the flexibility of PAN with CA was provided. Finally, in terms of ductility, PAN with CA was reported to have a higher ductility compared to PAN, suggesting that PAN with CA is better able to undergo plastic deformation before fracture. Overall, PAN excels in strength and flexibility, while PAN with CA is characterized by enhanced elasticity, stiffness, and ductility.

**Table 1.** Tensile results PAN and PAN with CA

| Formulation                            | PAN           | PAN + CA |
|--|---------------|----------|
| Tensile Strain at Maximum Load (%)     | 8.39%         | 1.33%    |
| Tensile Strain at Break (%)            | 23.79%        | 37.09%   |
| Modulus (MPa)                          | 15.03721      | 19.29410 |
| Tensile Extension at Maximum Load (mm) | 2.60049       | 0.41208  |
| Flexibility                            | more flexible |          |
| Ductility                              |               | higher   |

### Chemical and electrochemical properties

Fourier transform infrared (FT-IR) spectroscopy was employed to analyze the functional group content of the materials [7]. The composition of the electrospinning solution, including the cellulose chemical formula, is critical for evaluating compatibility and functionality, as well as its influence on nanofiber characteristics. This

includes the development of composite nanofibers aimed at enhancing flexibility and strength. Challenges related to the dissolution of cellulose in solvents have prompted investigations into combining cellulose with other materials to produce electrospun cellulose composite nanofibers, which are utilized across various industries [11]. Solutions lacking surfactants fail to produce fine, uniform jets due to the rapid evaporation of the solvent, unlike those with surfactants. Surface tension in these cases may lead to the formation of beads on the liquid jet [7]. Understanding the functional groups of each polymer and material in the electrospinning solution offers valuable insights for novel applications. Cellulosic materials, characterized by their 1D hierarchical structures and hydroxyl groups, have attracted considerable interest as natural bio-templates for the fabrication of lithium-ion battery (LIB) electrodes [12].

The electrochemical performance of cellulose electrospun nanofibers was assessed using a 4-point probe. A decrease in current at both peaks, indicative of reduced electrode surface conductivity, was observed when the membrane was placed onto the FTO substrate. This reduction may affect sensor sensitivity due to the insulating properties of cellulose acetate (CA) [13].

### Thermal properties

The TGA curve illustrates the sample deterioration in three distinct phases. The initial phase, occurring between 30 and 50 °C, involves moisture extraction from the sample. The second phase, observed between 250 and 400 °C, is marked by significant mass loss, during which nearly the entire sample deteriorates. In the final phase, above 400 °C, complete degradation of the nanofiber occurs, leaving only a minimal residue [7]. The data plotted on the graph is derived from continuous monitoring of the sample weight, coupled with the passage of specific gases and associated degradation processes.

## **POTENTIAL AND APPLICATION OF CELLULOSE ELECTROSPUN NANOFIBER IN ELECTRONIC FIELD**

Cellulose's sustainability, owing to its biocompatibility, biodegradability, non-toxicity, and environmental friendliness, has facilitated the development of various applications. Wearable electronic devices, which must be portable, self-powered, and highly efficient, have driven the advancement of several nanogenerator technologies, including those based on photoelectric, thermoelectric, piezoelectric, triboelectric, and moist-electric generation [14]. Recent research highlights the use of electrospun nanofibers in electrochemical devices such as solar cells, fuel cells, rechargeable batteries, supercapacitors, and hydrogen storage systems [15]. Many studies have focused on cellulose-based materials. The high surface-to-volume ratio and superior spinnability of cellulose acetate (CA) nanofibers enable the incorporation of numerous sensing elements, resulting in a rapid reaction time (30s) and high sensitivity across a concentration range from 200 ppm to 12,750 ppm. Integrating cellulose (and its derivatives) with electrospinning technology presents an effective approach for producing nanostructured porous materials with promising functionalities, flexibility, renewability, and biodegradability [16]. Notable applications of cellulose electrospun nanofibers in the electronics field include:

### **Bacterochromic cellulose sensor**

A novel smart biochromic textile sensor was developed by immobilizing anthocyanin extract into electrospun cellulose acetate nanofibers, enabling the detection of bacteria for various applications, including healthcare monitoring [3]. This sensor integrates cellulose acetate-based nanofibers with anthocyanin extracted from red cabbage to create a tactile-based bacterial biosensor. Upon exposure to an affected medium, the sensor exhibits colorimetric changes. The combination of low mass, high permeability, porosity, flexibility, and a broad surface area of the nanofibers

facilitates effective analyte contact, resulting in an inexpensive and highly sensitive diagnostic tool.

### **Cellulose-curcumin composite colorimetric sensor**

To monitor the real-time deterioration of raw chicken, electrospun regenerated cellulose nanofiber (RCA) composites coated with curcumin (CUR) (CUR-Cot) were developed. This novel method, particularly relevant to the food safety sector, employs cellulose-based nanofibers for sensor applications. Typically, sensing components, such as pigments or dyes, are integrated with support materials—including glass, film, nanofibers, cellulose, polyvinyl alcohol, starch, chitosan, and chitin—to create smart colorimetric sensors [2].

### **Mercury ions electrochemical sensor**

The development of rapid technologies for mercury detection is essential due to the hazards associated with environmental mercury contamination, which necessitates stringent control of this element [11]. Accurate measurement of mercury ions ( $\text{Hg}^{2+}$ ) in various matrices, including soil, water, air, and biological samples, is critical. To address this need, an environmentally friendly electrochemical sensor was developed for detecting mercury (II) ions ( $\text{Hg}^{2+}$ ). This sensor utilizes electrospun cellulose acetate nanofibers modified with silver nanoparticles (AgNPs) on fluorine-doped tin oxide (FTO) glass [13].

### **Solar-powered interfacial evaporation**

This article introduces a novel bio-based nanofibrous foam designed for solar interface evaporation with exceptional efficiency. To achieve this, an in-situ layer-by-layer self-assembly process combined with electrospinning was employed to fabricate a hybrid membrane composed of cellulose nanofibers and graphene oxide (GO). The principle of solar-driven interfacial evaporation involves using an evaporator to convert solar energy into heat, which is then concentrated at the

evaporation interface to generate water vapor. Utilizing cellulose and a straightforward three-step synthesis process, a unique three-dimensional Janus-type nanofibrous foam evaporator was developed. This evaporator effectively absorbs solar energy and facilitates water pumping across various foam layers [17].

#### 4.5 Lithium-ion battery separator

The rapid advancement in lithium-ion battery (LIB) technology has led to its widespread application in both portable electronics and large- and medium-scale energy storage systems [12]. This study presents a novel composite membrane consisting of electrospun poly(vinyl alcohol)/melamine (PVAM) nonwoven membranes sandwiched between zeolitic imidazole frameworks-67 (ZIF-67) decorated cellulose acetate nanofibers (ZIF-67@CA). The separator plays a crucial role in enhancing the lifespan of LIBs by providing ion transport pathways between the cathode and anode and preventing electrical short circuits [5]. This novel composite nonwoven membrane demonstrates potential for use in lithium-ion battery systems, offering high power and safety, making it particularly suitable for electric vehicles (EVs) [8].

#### Based templates for lithium-ion metal electrodes

The electrospinning method was employed to fabricate nanoscale cellulosic fiber templates, which were subsequently used to develop one-dimensional hollow TiO<sub>2</sub> electrodes [12]. The exceptional electrochemical performance of these electrodes is attributed to their unique hollow nanostructure and optimized phase, which contribute to a large BET surface area and enhanced ion diffusion.

#### Enhancement of triboelectric generator performance

The triboelectric nanogenerator (TENG) represents a promising technology for mechanical energy harvesting, characterized by its low cost, high efficiency, and straightforward production process [18].

The control of nanofiber diameter can be precisely achieved by adjusting humidity, which affects the surface morphology, roughness, and frictional contact area of triboelectric materials through the electrospinning process [19].

#### Moist-induced electricity generators (MEGs)

The combination of enhanced hydrophilicity increased specific surface area, and reduced pore size enabled a single MEG derived from the optimized CA membrane to achieve an output voltage of approximately 700 mV and a maximum output power density of 2.45  $\mu\text{W cm}^{-2}$  [14]. To develop an affordable, effective, and wearable MEG, a novel tree-like structure cellulose acetate (CA) nanofiber membrane was fabricated using a one-step electrospinning process involving CA solutions and organic branched salt.

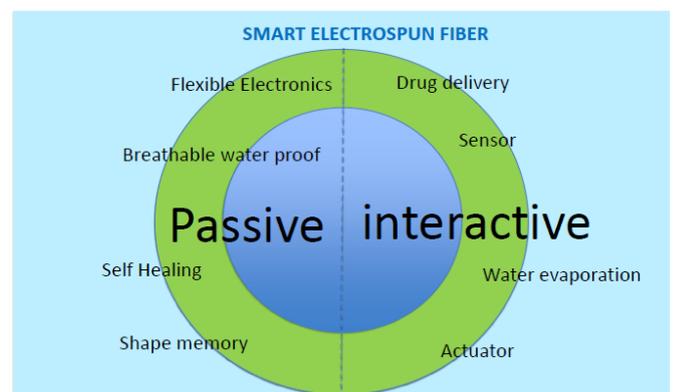
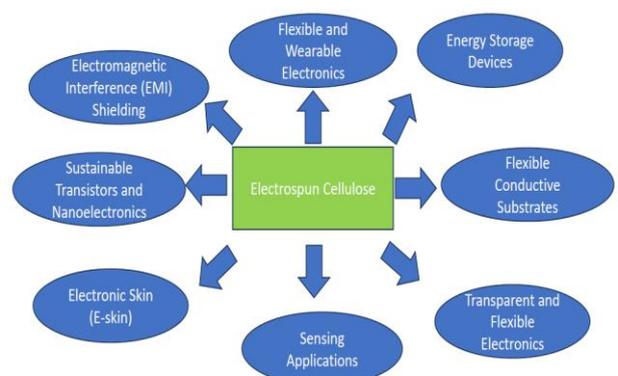


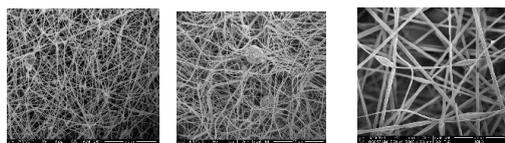
Fig. 3. The potential and application of electrospun nanofibers



**Fig. 4.** The potential and application of cellulose electrospun nanofibers in the electronic field [20].

## CHALLENGES

Cellulose electrospun nanofibers present several challenges in their application. Methodologically, while nanofiber-based electrodes demonstrate exceptional rate capability and cycle stability, large-scale industrial manufacturing faces significant hurdles due to the slow production rates associated with electrospun nanofibers [15]. This low productivity stems from the optimized electrospinning conditions, which involve low flow rates during spinning and generally low polymer concentrations in the spinning solutions [16]. To address these issues, new electrospinning units with advanced features have been developed. These innovations aim to overcome the challenges while capitalizing on the high porosity, low density, and large specific surface area of electrospun nanofibers, a technique that proves formidable in creating nanofiber nonwovens and sponges with a wide range of potential applications [21].



**Fig. 5.** Shows the different optimised nanofiber morphology of the fibres during the solidification. Fibres that are (a) PAN; (b) CA; (c) PAN with CA .

Despite the advantageous properties of cellulose nanofibers, optimization of their composition for electronics and energy-related applications remains limited. To date, no studies have systematically compared the morphological, rheological, and mechanical properties of cement composites incorporating cellulose nanofiber (CNF) suspensions from various sources, which differ in quality and uniformity, including mixtures of thick and thin fibers [23]. Cellulose derivatives, with

their structural modifications, exhibit significantly higher solubility in a wide range of chemical and inorganic solvents compared to cellulose itself [16]. Therefore, to prevent defects, as depicted in Figure 3 [22], it is crucial to optimize the electrospinning solution, methodology, and fabrication processes.

## FUTURE DIRECTIONS

In the field of electronic materials for devices and technology, energy-related applications such as energy storage, energy conversion, and conductive materials are likely to attract significant attention regarding the prospects of cellulose electrospun nanofibers. Understanding the importance of a three-dimensional porous structure in flexible support materials for developing conducting electrodes, cellulose and its derivatives demonstrate great potential with the emergence of numerous electro-conductive materials [16].

Cellulose acetate has emerged as a key material for developing flexible and durable non-composite and composite conductive materials, owing to its straightforward manufacturing process via electrospinning. Its higher solubility compared to cellulose makes cellulose acetate (CA) a frequent choice in the production of electrospun nanofiber membranes [14]. While a detailed cost assessment remains necessary, electrospun webs of CA and deacetylated CA are suggested as promising electrolyte membrane materials for dye-sensitized solar cells [24]. The application of simple electrospinning techniques combined with cellulose-based materials for creating electrolyte membranes, electrodes [12, 14, 18, 19], and semi-conductive or conductive materials opens avenues for advancing knowledge and enhancing the potential of cellulose electrospinning within the electronics field.

## CONCLUSION

Cellulose electrospun nanofibers exhibit considerable potential as future materials for

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electronics and conductivity applications, leveraging the sustainable properties of cellulose and its derivatives alongside the electrospinning technique. The methods of characterization are critical, as they impact the accuracy and ability to diagnose both successful outcomes and issues related to the developed materials. Although challenges related to scalability and material optimization for specific applications may limit short-term utilization of cellulose-based electrospun nanofibers, ongoing research and solution optimization have the potential to drive significant advancements in nanomaterials development and related industries. The advancement of electronics and energy-related technologies is increasingly vital, offering substantial benefits for current and future technological applications.

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